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Mobile System for Extracting Spilled Hazardous Materials from Excavated Soils

Rexnord, Inc., Milwaukee, WI

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Municipal Environmental Research Lab.
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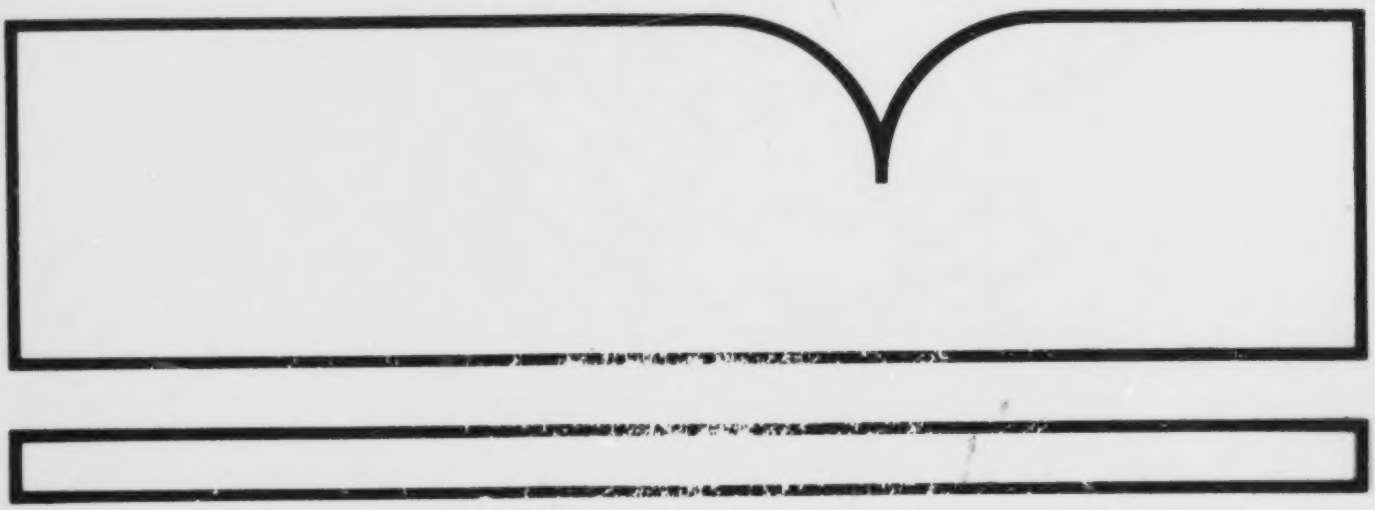

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16. ABSTRACT

Laboratory tests were conducted with three separate pollutants (phenol, arsenic trioxide, and polychlorinated biphenyls (PCB's)) and two soils of widely different characteristics (sand/gravel/silt/clay and organic loam) to evaluate techniques for cleansing soil contaminated with released or spilled hazardous materials. The tests show that scrubbing of excavated soil on site is an efficient approach for freeing soils of certain contaminants but that the effectiveness depends on the washing fluid (water + additives) and on the soil composition and particle size distribution. Based on the test results, a full-scale, field-use system was designed, engineered, fabricated, assembled, and briefly tested; the unit is now ready for field demonstrations. The system includes two major soil scrubbing components: a water-knife stripping and soaking unit of novel design for disintegrating the soil fabric (matrix) and solubilizing the contaminant from the larger particles (>2 mm) and an existing, but re-engineered, four-stage countercurrent extractor for freeing the contaminants from smaller particles (< 2 mm). The complete system requires auxiliary equipment, such as the EPA-ORD physical/chemical treatment trailer, to process the wastewater for recycling; under some circumstances, provision must be made to confine and treat released gases and mists. The processing rate of the complete system is 2.3 to 3.8 m^3/hr (4 to 5 yd^3/hr), though the water-knife unit (used alone) can process 11.5 to 13.5 m^3/hr (15 to 18 yd^3/hr).

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MOBILE SYSTEM FOR EXTRACTING SPILLED HAZARDOUS MATERIALS FROM EXCAVATED SOILS

by

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Contract Number 68-03-2696

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report describes the laboratory feasibility investigations and the design and construction of a full-scale, mobile system for treating excavated, contaminated soils at a field site by sieving, disintegrating the soil matrix, and cleansing the soil of hazardous chemicals. The system is expected to take its place among other emerging methods such as in situ treatment or incineration, for treatment of contaminated soils at the actual site of a release under a wide variety of circumstances.

Francis T. Mayo
Director
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ABSTRACT

Laboratory tests were carried out with three different pollutants (phenol, arsenic trioxide, and polychlorinated biphenyls [PCB's]) and two soils of different character (gravel/sand/silt/clay soil and organic loam topsoil) to evaluate a technique for the scrubbing or cleansing of soils contaminated with hazardous materials. The results of the tests were used in the design and construction of a full-scale system for field evaluation in cleaning excavated contaminated soils. The system employs two major soil scrubbing components: a newly designed water-knife, screen stripper, and soaking unit for breaking up soil lumps and stripping chemicals from larger particles (<2.5 cm but > 2mm in diameter); and a countercurrent chemical extractor for washing the smaller particles (<2 mm)that pass through the screens. The complete soils scrubbing system also requires the use of a wastewater treatment system to permit recycling of the washing fluids and an air cleaner when gases are evolved. The projected processing rate of the complete system is 2.3 to 3.8 m^3/hour (3-5 yd^3/hr). (Treatment ratesrange from 11.5-13.5 m^3/hr (15-18 yd^3/hr) when only the water-knife unit is needed.) Treatment residues consist of skimmings from froth flotation, a mixture of washed gravel, sand, and organic detritus discharged from the knife-screen unit, fine particles from the extractor, the spent washing fluids, exhausted carbon, and the other treatment products (flocs, sediments).

A potentially limiting constraint on the treatability of soils is their clay content, since clays generally are good adsorbers and the particles may not be so effectively scrubbed as are sands. In particular, clay lumps that are only surface contaminated should be removed before full disintegration is accomplished (since the uncontaminated particles could then function as adsorbents and lower the efficiency of the cleansing). Contaminant-saturated consolidated clay lumps, upon disintegration, will release pollutants, however. Most inorganic compounds, almost all water soluble or readily oxidizable organic chemicals, and some partly miscible-in-water organics can be treated with water or water plus an additive.

During limited laboratory extraction tests, phenol was very efficiently removed from both organic and inorganic soils, whereas PCB and arsenic oxide clung more tenaciously to the soils and were released far less readily into the washing fluids. Until acceptable limits of residual concentrations in the washed soil are agreed upon, the utility of the soil washer in a particular situation cannot be assessed. Laboratory tests did show that soil scrubbing vastly speeds up the release of chemicals from soils, compared with the much slower rate that occurs under natural leaching conditions.

A full-scale soil scrubber has been constructed and tested and is ready for further demonstration. The cleansed soil can be returned to the site from which the contaminated soil was excavated.

This report was submitted in fulfillment of Contract No. 68-03-2696 by Rexnord, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period December 1976 to April 1982, and work was completed as of November 1982.

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SECTION 1

INTRODUCTION

NEED FOR NEW TECHNOLOGY

The leaching of hazardous materials from contaminated soils into groundwater is recognized as a potential threat to the nation's drinking water supplies. Such situations occur as the result of accidental spills of hazardous substances and as releases from the many uncontrolled hazardous waste disposal sites now known to exist throughout the country. Current corrective technology is largely limited to the excavation and transfer of such soils to suitably sealed or lined landfills where uncontrolled leaching cannot occur.

Onsite treatment can often be a more cost-effective solution to the problem, and avoids the need for transporting hazardus wastes. Research projects have demonstrated, for example, that contaminated soils can be isolated by grouting, slurry-wall trenching, installation of steel piling, etc., and then subjected to in-situ leaching for treatment. The effectiveness of such processes is limited by, among other factors, the permeability of the soil in its undisturbed state.

An alternative process is desirable for those situations in which soil permeability or other factors prevent effective cleanup by in-situ leaching. This proposed technology, the subject of the current effort, consists of excavation onsite, above-ground treatment of the contaminated soil, and return of the treated soil to its original site. Excavation of the soil from its natural state opens a number of options for improved separation of contaminants through better mixing and the ability to use different solvents. Such cleanups can also be carried out more quickly than they could with the in situ leaching of a more or less compact natural soil. An integrated engineered approach also makes it possible, or more convenient, to incorporate the controls needed for air emissions and/or treatment of the contaminated wastewaters generated by the process.

In passing, one may note that, once a soil is excavated, cleanup is not restricted to the washing approach described herein. Washing with organic solvents, processing with fluids at or above their critical points, wet air oxidation, incineration, and other flushing and/or disintegrative processes may be applicable. The prospective costs associated with each approach must be based on a specific situation; it is not realistic to assume that there is any universal "best" approach in terms of either cost or effectiveness.

The purpose of this project was to carry out appropriate laboratory studies and then design and construct a system capable of treating a wide range of excavated contaminated soils. Ideally, the resulting system will be useful for the correction of long-standing contamination problems (waste disposal sites), as well as for emergency cleanup of spills.

SELECTION OF WASHING FLUIDS

A variety of washing fluids can be used to cleanse contaminated soil, depending on the nature and properties of the chemicals to be removed and of the soils themselves. An effective treatment fluid or solvent must have these characteristics:

1. Favorable separation coefficient for extraction.
2. Low volatility under ambient conditions.
3. Low toxicity.
4. Safety and ease of handling in a field situation.
5. Recoverability.

Desirable Characteristics of Fluids

Favorable Separation Coefficient--The contaminant must be soluble in the solvent and the solvent itself easily separated from the soil. The higher the solubility of the contaminant in the fluid, the lower the volumes required for extraction. The solvent should be effective for a large number of contaminants and a wide variety of mixed hazardous substances.

Low Volatility--The solvent should not be extremely volatile, especially under ambient conditions, nor should it be flammable. Excessive volatility could result in significant solvent losses into the air and in causing hazardous situations for operating personnel.

Low Toxicity--The contaminant to be scrubbed from the soil poses a potential exposure hazard to treatment system operators, especially during those steps of the process that are intended to reconcentrate the contaminants, e.g., in the processing of spent extraction fluids. A treatment fluid should not subject treatment operators to unnecessary, additional hazards. The quantity of treatment fluid in the treatment system at any one time will probably be many times greater than the amount of contaminant. The exposure hazards from contaminants and treatment fluids will chiefly consist of skin and eye contact diseases and inhalation effects.

Safety and Ease of Handling--When a mobile system incorporates potential ignition sources such as an internal combustion engine generator and an electrical power system, special equipment design and operational procedures are required to minimize the potential for fire and explosion in the presence of flammable and/or explosive mixtures, contaminants, or treatment fluids. The transport and handling of such fluids is of equivalent concern.

Recoverability--The spent treatment fluids must be recoverable in a field-oriented treatment system so that cleaned fluids can be recycled and ultimately disposed of in an uncontaminated form.

Types of Cleaning Fluid

Assuming that most contaminants can be classified as either organic or inorganic, three basic solvent systems can be identified:

1. Water only.
2. Water plus an additive.
3. Organic compounds (neat or as mixtures).

When the system uses water or water plus an additive, most inorganic compounds, almost all water soluble or oxidizable organics, and some partially miscible-in-water organics can be treated. The important steps involve obtaining good contact (high mixing energy) between the soil and water and using the optimized amount of additive. These additives may include:

1. Acids to improve removals of metal salts and oxides.
2. Bases to enhance safety and removel for cyanide compounds, solubilize phenolics, etc.
3. Oxidants to aid in organic and reducing agent treatment.
4. Surface active agents to increase solubility of organics in the water phase.

Organic solvents allow more effective removal of organic contaminants, which action is a crucial consideration for compounds that have low water solubility. However, handling these materials in a field situation can be extremely difficult. Most are volatile and many are flammable. An organic solvent such as hexane or Freon may not be effective for all contaminants, or may extract humectic components and harmless organics from the soil and lead to a fouling problem with washing fluids and components. Organic solvent mixtures present special problems in recovery and reuse. Finally, adapting field equipment for use with an organic solvent is, at best, extremely difficult and costly. The advantage of using organic solvents to remove certain organic contaminants did not appear to outweigh the significant disadvantages of organic solvents for a system of the size and cost contemplated. For these reasons, this project concentrated on the development of soil washing technology that employs water plus an additive as a washing fluid.

When the unit is constrained to use water+additive washing fluids, the removal effectiveness for organic contaminants may be poor. Soil washing with water is most efficient for compounds with a high water solubility and a greater affinity for the water than the soil. This situation makes the soil scrubber most efficient with short-chain organic compounds, other organics with a relatively high water solubility, and inorganics that are rather soluble in water. The inorganic removal efficiency may decrease in those instances where the compound has a strong affinity for the soil components, especially, clays. This phenomenon may be critical for pollutants that are chemically sorbed onto certain soil types.

Acceptable discharge levels will determine whether on site soil washing is an appropriate treatment method for any particular contaminant. The "clean"

soil contaminant levels will certainly vary with the chemical involved. For example, treatment of an alcohol to a parts-per-million level may be acceptable while pesticide by-products may require treatment to the low parts-per-billion range before environmentally safe discharge of the soil. When evaluating the potential usefulness of a washing process, these levels of cleanliness must be defined beforehand. It may also be practical to scrub the soil to a contaminant concentration level that will reduce the grade of landfill required for disposal, i.e., from a hazardous landfill to a sanitary landfill.

Care must also be taken to avoid compounding problems when scrubbing soil. Transfer of contaminant to the water phase and subsequent water treatment will often result in a solid waste for eventual disposal. The residual may be spent carbon or a treatment sludge and the volumes involved may be quite large. Problems and costs associated with disposal of these residues should not exceed those that would have been encountered when handling the contaminated soil alone.

CONCEPTUAL APPROACH TO SOIL SCRUBBING

A review of available literature on soil systems, soil/chemical interactions, and treatment procedures produced little directly applicable information. It was necessary to rely on the past experience in soil handling and treatability of the project team and on common sense in order to establish reasonable limitations and to identify the potential applicability of a particular technique.

A simplified schematic of the basic operations involved in soil scrubbing is shown in Figure 1. The first step in soil washing involves excavation of contaminated soil, which can be accomplished using various types of construction machinery and earth-moving equipment. The removed soil must be reduced in size and the soil structure or "fabric" disintegrated to allow effective contact between the solvent and soil particles.

This type of pre-conditioning requires mechanical action on a wide variety of soil types. After size reduction, the appropriately conditioned soil is then ready for actual treatment in the scrubber.

The treatment action involves two mechanisms:

1. Physical stripping of that portion of the contaminant that is not tightly bound to the soil particles. The contaminant may have filled void spaces and be physically trapped in the soil system. Removal can be effectively accomplished by stripping the contaminant from the soil, possibly by using high pressure fluid rinsing.

2. Extraction of the tightly bound contaminant from the soil into a solvent. This step allows transfer of the contaminant into a phase more easily handled using conventional treatment processes. The extraction efficiency may be increased by applying a countercurrent approach and solvent use can be optimized if solvent treatment and recycle are utilized.

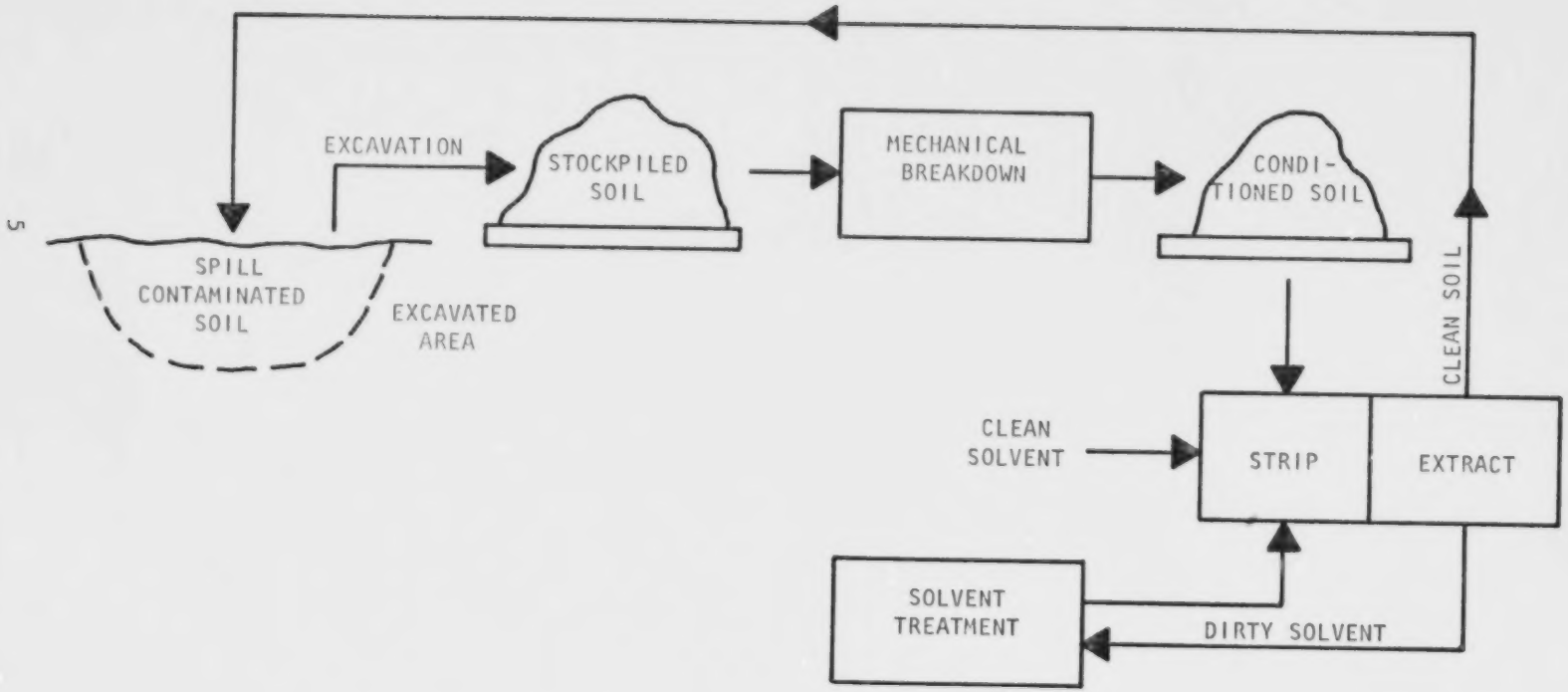


Figure 1. Schematic of soil scrubbing operations.

The soil scrubbing approach is quite simple; however, there are significant difficulties involved in applying these concepts to complex situations of soil contamination. Soil types vary considerably both in their physical characteristics and attraction for different contaminants.

SOIL TREATABILITY POTENTIAL

The varied geologic history throughout the United States has resulted in complex combinations of near-surface soils, as exhibited by their wide range of chemical constituents, gradations, and organic content. These variables affect the soil treatability potential.

The treatability potential of any soil can be considered a combination of its physical handling and sorption/desorption characteristics. For example, it may be technically feasible to desorb a particular contaminant from a clay soil, but the mechanical effort and energy required to disintegrate the clay to a particle size that allows the contaminant to be desorbed efficiently may result in low cost-effectiveness and low treatability potential.

The wide variety of qualities encountered in the soil systems can adversely affect the processing equipment. Major difficulties or limitations can result from:

1. The gradation of the soil particles, primarily the predominance of large objects such as rocks or boulders. Large rocks, boulders, tree roots, and branches cannot be easily broken down by conventional size reduction equipment; they should, therefore, be presorted and disposed of separately.

2. The clay content of the soil, primarily as related to large zones of clay or cohesive materials. The cohesive and plastic nature of most clays, combined with their very small particle size, makes it difficult to rapidly break them down into treatable sizes. Most conventional size reduction systems are designed to handle only a certain maximum percentage of clay within a soil structure. Clays can be broken down by freezing or drying combined with impact or crushing techniques. However, these methods are energy intensive and, in general, are not very practical for high volume materials handling systems. Note that the plasticity of the clay results in a low permeability so that the potential impact of a contaminant spill on clay is much less than on a sand or gravel soil, unless the clay is finely divided and dispersed (large surface-to-volume ratio).

   The percentage of clay will directly affect the rate of soil treatment both at the pre-treatment stage and during the chemical treatment phase itself. Although this limitation of clay within a soil system is significant, throughout most of the United States, use of the scrubber unit is feasible and adaptable.

3. The root system typically developed in a thick topsoil can foul many mechanical systems designed to break down soil into more easily

handled sizes. Roots tend to be flexible and resilient, and wind around most rotation devices. A common example which is understood by gardeners is the way in which roots tend to wind around the shaft of a rototiller. Large tree roots or branches are also difficult to process with conventional soil handling systems because of their bulk and resistance to breakdown.

Desorption Characteristics

The soil/chemical interactions that affect sorption/desorption are complex. The desorption of a contaminant from a soil is related to, though not necessarily a direct function of, the sorptive ability. Adsorption onto a soil surface is a phenomenon based upon physico-chemical equilibrium conditions between the contaminant, soil water, and soil itself. The solubility of the contaminant in water and the reactions between the contaminant and the soil components determine the equilibrium that is established.

Researchers have evaluated attenuation or adsorption of contaminants in soils rather than contaminant desorption (much work has been done on modeling dispersion/diffusion of pesticides in soil). Although the sorption/desorption relationship is not well-established, the generalities and methods of adsorption may be appropriate for a basic understanding of desorption. The existing research does suggest the following unquantified relationship:

$A = f(C, pH, Or, Co, t)$. The definition of the parameters follow.

"A" is the attenuation of a given contaminant by the soil in question, expressed as percent removed from solution. Attenuation is proportional to five parameters, the first being the clay factor "C". The clay factor, in turn, is a function of four, interrelated factors:

1. clay content of the total soil volume
2. type of clay mineral in the soil
3. exchange capacity of the clay
4 specific surface area of the clay.

The directly proportional functional relationship between attenuation and increasing clay content implies an inverse relationship between attenuation and an increasing content of granular material in the soil.

The term "pH" refers to the pH of the soil/contaminant environment. This includes both the contaminant waste stream and the natural soil pH conditions. The attenuation is affected by the pH of the leaching solution and is a function of the specific contaminant and the retention mechanism involved in its removal from solution.

"Or" is the organic content of the soil. The organic content is most important when evaluating organic contaminants that tend to readily adsorb onto organic matter in the soil. Whether the organic matter is in the form of living roots or dead decaying material may be important because of the differences in structure and composition.

"Co" is the contaminant concentration factor. At low levels, the concentration of the waste stream may influence the attenuating mechanism operative in the soil system. However, the situation is somewhat different at high contaminant concentrations. The soil, in many cases, may be incapable of attenuating the applied dosage even when all of the factors needed are present, simply because it does not have the required surface area or sufficient exchange capacity.

The term "t" is a time factor. Attenuation is directly related to the contact time between the contaminant and the soil, all other conditions being constant. The attenuation achieved during a given contact time should be proportional to the permeability of the soil. The permeability of the soil is directly related to its grain-size distribution, which ties in with its mineralogical composition.

Soil contamination situations can be grouped into two types as differentiated by a time factor: immediate problems and long-term situations. A spill occurrence is a problem which, when responded to immediately, involves only a short contact time between soil and contaminant. Long-term situations of soil contamination, on the other hand, result from initially untreated spills or from improper chemical waste disposal practices.

The contaminant contact time defines the rate at which equilibrium will be established. For spill situations in which the contaminant can be relatively quickly contained or removed, the soil/chemical interactions may be minimal. Conversely, in a long-term situation where leachate slowly leaks from a landfill, the soil/chemical equilibrium reactions may be well-defined and established.

The time effects are most prevalent in cohesive or clay-like soils. Since the permeability and flow rate are low in a clay or silt structure, the contaminant will require a longer time to contact the soil and to be adsorbed onto the soil surface. With time, the amount adsorbed will increase and the subsequent time for desorption may also increase. In a sand or gravel soil, on the other hand, a spill will flow almost immediately through the soil structure, contacting the soil surface and moving quickly onward. In this latter situation, the effects of time are less significant.

PROJECT OBJECTIVES

The purpose of this project was to develop and construct a mobile system for demonstration of the extraction of hazardous materials from spill-contaminated soils. The goals of the soil-scrubbing system are threefold:

1. To clean contaminated soil sufficiently to make it suitable for redepositing into the place from which it was removed

2. To separate hazardous materials from the extracting fluids to the extent that the fluid is non-contaminated

3. To recover the hazardous material in such a form that it can be handled, reprocessed, and/or disposed of by environmentally acceptable methods.

This project did not explore technology for breakdown of large soil lumps in any detail. Rather, the assumed inlet situation was free-flowing soil which an entry screen would restrict to 2.5-cm (1.0-in.) particles or smaller. The project did not address the spent washing fluid treatment system, which will probably consist of a physical/chemical treatment system such as EPA possesses and has already demonstrated for field use (14). Cleaning of the air contaminants generated by the process was not addressed, except to provide containment of these emissions with connections for ducting to an appropriate air cleaner. The primary emphasis of this project was on the scrubber itself, specifically on those components that permit soil particles to be effectively washed through physical and chemical reactions.

Prior to design and construction, alternative approaches were evaluated and selected approaches were tested on a laboratory scale. This report discusses those evaluations and their influence on the ultimate construction of the components for demonstration.

SECTION 2

CONCLUSIONS

The following conclusions can be drawn from the work carried out during this program and the knowledge gained during that effort:

1. Spill-contaminated soils can be excavated and treated onsite, using extraction with water or aqueous solutions for many pollutants frequently encountered in such situations.

2. A system capable of decontaminating 2.3 to 3.8 m^3/hr (3-5 yd^3/hr) of soil has been designed and constructed and is now available for field testing by the U.S. Environmental Protection Agency (EPA). If finer (<2mm) are absent or do not require treatment, the processing rate (water-knife drum screen unit) is 11.5-13.5 m^3/hr (15-18 yd^3/hr).

3. Water knives function as a compact and economical means of achieving effective contact between contaminated soil particles and extractant.

4. Countercurrent extraction is effective in removing certain adsorbed contaminants from soils and, for the size of equipment needed, hydrocyclones are the preferred devices for separating the extracted solids from the extractant.

5. Laboratory experiments demonstrate that soil characteristics (particle size, distribution, organic content, pH, ion-exchange properties, etc.) are very important factors in the removal of contaminants.

6. In addition to the percent-contaminant removed, the allowable level of pollutant remaining in the soil is an important consideration in determining when adequate decontamination has been achieved, since the final concentration affects the options available for disposal of the residual solids.

SECTION 3

RECOMMENDATIONS

Based on the observations made during this investigation, several suggestions are offered for future work.

1. Laboratory screening tests should be performed on a wider range of typical compounds and mixtures encountered in hazardous substance spill and release situations to ensure that high levels of decontamination can be achieved with this process. Conversely, lab tests should be performed before the complete system is field-mobilized.

2. The results of this study apply primarily to spill situations. Contaminated soils found at waste disposal sites may exhibit different extraction characteristics because of the extended soil/contaminant contact time and of weathering and in situ reactions. Studies are needed to establish whether and to what extent such changes affect the decontamination process.

3. Other extractant solutions and solvents should be explored to learn whether the efficiency of the process can be improved without damaging the equipment or increasing the hazards to which the workers may be exposed.

4. A wider range of soils should be examined to determine what changes in the system are practical to better cleanse soils with characteristics (e.g., greater cohesiveness and adsorptive properties of clay- or silt-rich soils) that differ significantly from those of the soils already tested, and to evaluate the tendency of disintegrated clay (clay particles) to function as adsorbents.

SECTION 4

SELECTION OF SCRUBBING METHODS, SOILS, AND CHEMICALS FOR TESTING

As the first stage in the development of a soil scrubber, it was necessary to make preliminary scrubbing equipment choices and to experiment with these methods on a laboratory scale using selected chemicals and soils.

Physical Stripping

The first step in the processing train involves physical stripping of contaminants that are not physically or chemically adsorbed on the soil particles. Since a significant amount of contaminant could be entrained in soil void spaces, this effort may result in high treatment efficiencies. However, since pretreatment devices would probably not be capable of fully breaking down soil lumps, a secondary objective for this equipment involves further size reduction below 2.5 cm (1.0 in.) in diameter.

Both contaminant stripping and lump breaking require a relatively high level of energy input for the greatest efficiency. Several systems were evaluated and all but one were eliminated from further consideration. Commercially available rotary scrubbers were eliminated because the action of the slowly rotating cylinder was not considered sufficiently energetic to perform stripping and lump breakdown. The log washer, generally used in the aggregate industry for washing clay and silt from sand or gravel, was also evaluated. The device is basically an inclined rotating screw conveyor with internal beater paddles that increase the cleaning action. Unfortunately, the rotational speed of the arms is quite low, which reduces the unit's effectiveness in breaking down clay lumps. In addition, the equipment requires large volumes of water for proper operation, a condition that could significantly impact its ultimate usefulness in the field.

The attrition scrubber uses high energy scrubbing forces applied by a dual propeller mixer. The pitches of the two blades are opposed, which causes a substantial amount of mixing turbulence. An attrition scrubber is intended for use on sand-size particles and may not be suitable for breaking down clay lumps. Efficient use of this device requires feed concentrations of 70-percent solids, which is a difficult constraint to meet in a natural soil system contaminated with chemicals. Wet soil can foul the unit and cause serious operational difficulties. A large amount of gravel in the soil will cause undue wear and vibration on the equipment. Also considered but rejected were: horizontal vibrating screens, fixed blade mixers, concrete mixers, aggregate scrubbers, ball mills, jaw crushers, hammermills and non-clog hammermills (1).

Another high energy system uses water knives to create a powerful fluid stream for contaminant stripping and lump breakdown. The water knives are small, flat-blade nozzles that function by creating a high velocity stream of water in the shape of a long narrow line (Figure 2). Washing is performed by directing the nozzle stream at a moving layer of material. The relative motion between nozzle and material can be achieved by:

1. Moving the material past a stationary nozzle on a conveying mechanism.
2. Moving the nozzle over the top of a stationary layer of material.
3. Moving the material on a conveyor and moving the nozzle over the material.

The knife-like hydraulic action is achieved by a combination of the force and thinness of the water stream. The washing is instantaneous. The contact of the knife with the material can be so gentle that it can clean peaches, or it can be so "sharp" that it will strip scale layers from steel. In the soils scrubbing application, the water knife seemed capable of both lump breakdown and scrubbing. The volumes of water and pressures needed for proper nozzle operation can be estimated from design parameters; however, the actual effectiveness of the scrubbing technique for treatment must be determined from laboratory testing.

Extraction and Separation

Small soil particles will most likely be more affected by chemically bound contaminants than large particles. As a result, the physical stripping process alone may not be effective for treatment of small particles, and an additional step may be necessary. Chemical extraction in a countercurrent mode was chosen as a treatment method. This process is carried out in a series of extraction steps in which the contaminated soils are given sufficient time to contact solvents of increasing purity. A schematic of a simple system incorporating two extraction steps is shown in Figure 3. The purpose of countercurrent extraction is to maximize the concentration gradient between the soil and the solvent while minimizing the volume of solvent required through solvent reuse. Therefore, the flow of soils from step to step is opposite to the flow of solvents, thus the name countercurrent.

Besides the extraction tanks, the countercurrent extraction system also requires solid/liquid separators after each extraction step. Various units may be applicable, including centrifuges, belt presses, vacuum filters, filter presses, and hydrocyclones. A gravity separation procedure could also be used between extraction stages but is likely to be inefficient, time consuming and, therefore, impractical. Centrifuges and filters are often limited by solids loading and are extremely expensive, very large, and often difficult to operate. They do perform efficient separations; however, they are not suitable for multiple separations in a mobile unit.

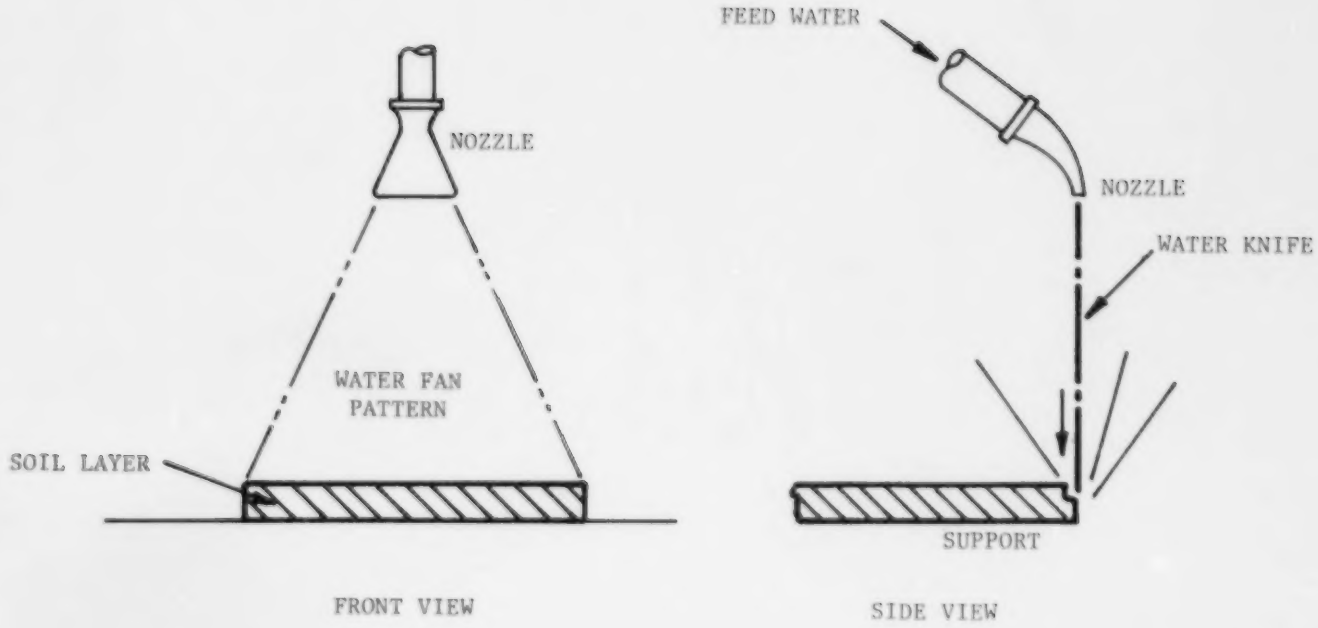


Figure 2. Schematic of the water knife used for chemical stripping and lump breakdown.

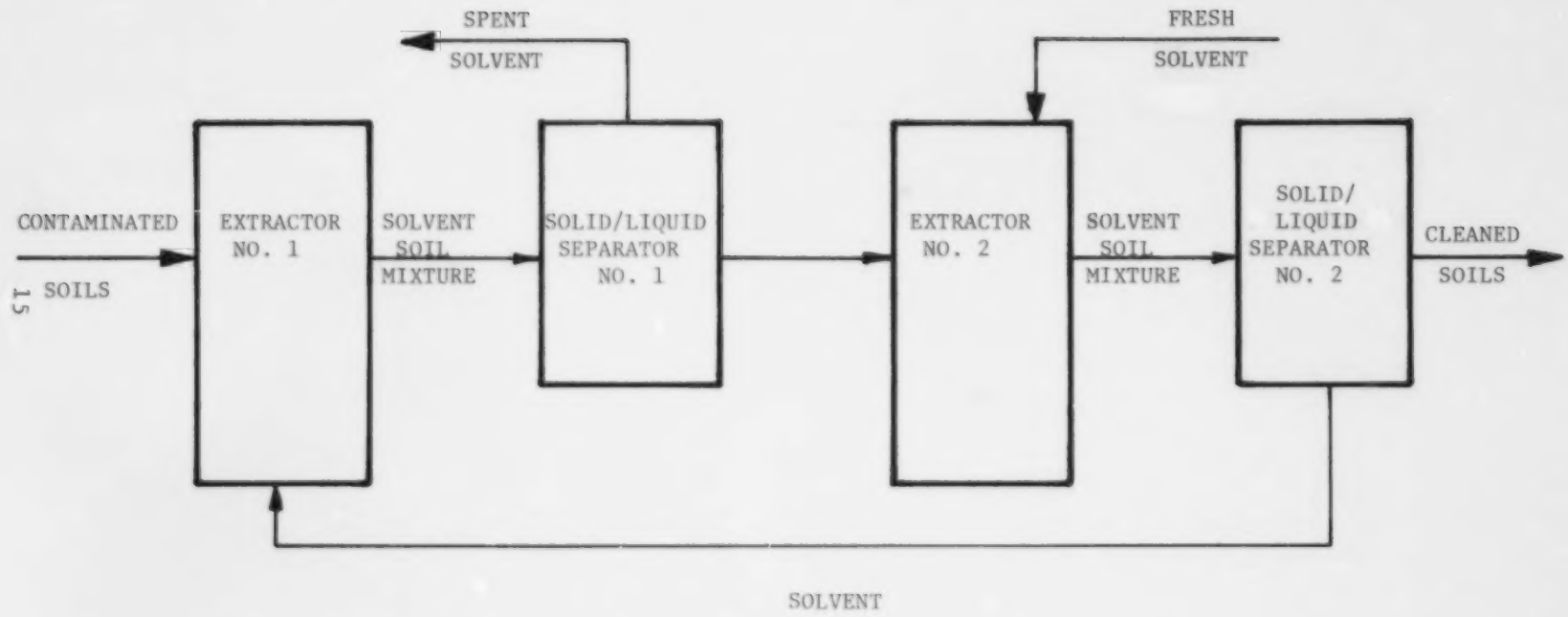


Figure 3. Schematic of counter-current extraction system with two extractions.

The hydrocyclone, on the other hand, is less efficient but has a high capacity and relatively low cost. It utilizes fluid pressure energy to create centrifugal fluid motion, permitting separation or classification of suspended solids. It is also capable of separating fluids of different specific gravities. A sketch of a commercially available hydrocyclone is shown in Figure 4. Feed slurries enter a tangential inlet at the top of the device, then spiral their way around the cylindrical walls proceeding downward. Centrifugal separation occurs during the period of spiraling and those materials having a higher specific gravity migrate toward the outer walls. When the spiral flow reaches the lower part of the cyclone it undergoes a direction change and begins to spiral upward toward the outlet. The result is a spiral within a spiral. The materials along the outer wall of the cyclone do not participate in this inner spiral action but, rather, continue downward where they are discharged either continuously or intermittently from the bottom of the cyclone. The solids concentration in the outlet streams vary with, among other things, influent solids type and concentration, particle size, specific gravity, and fluid viscosity. Hydrocyclones do "lose" some fine solids in the overflow. The amount of material discharged in this manner and its impact on treatment efficiency requires definition by lab testing. Mixing and chemical contact of particles with the solvent are enhanced by the action of the hydrocyclone.

CHEMICAL SELECTION

Once the preliminary scrubbing equipment choices were made, it was necessary to choose contaminants and solvents to be used in the preliminary laboratory testing.

Contaminant Choices

Four major criteria were addressed to select contaminants for preliminary laboratory testing. These criteria are that the selected chemicals should be:

1. representative of a wide range of contaminants that could impact soils systems.

2. classified as hazardous and presenting a high risk of spillage.

3. involved preferentially in existing soil-contamination problems, which could be partially or completely alleviated by successful soil scrubbing.

4. chosen to span the range of difficulty of removal.

On the basis of the above contaminant-selection criteria, the following three contaminants were selected for preliminary laboratory testing:

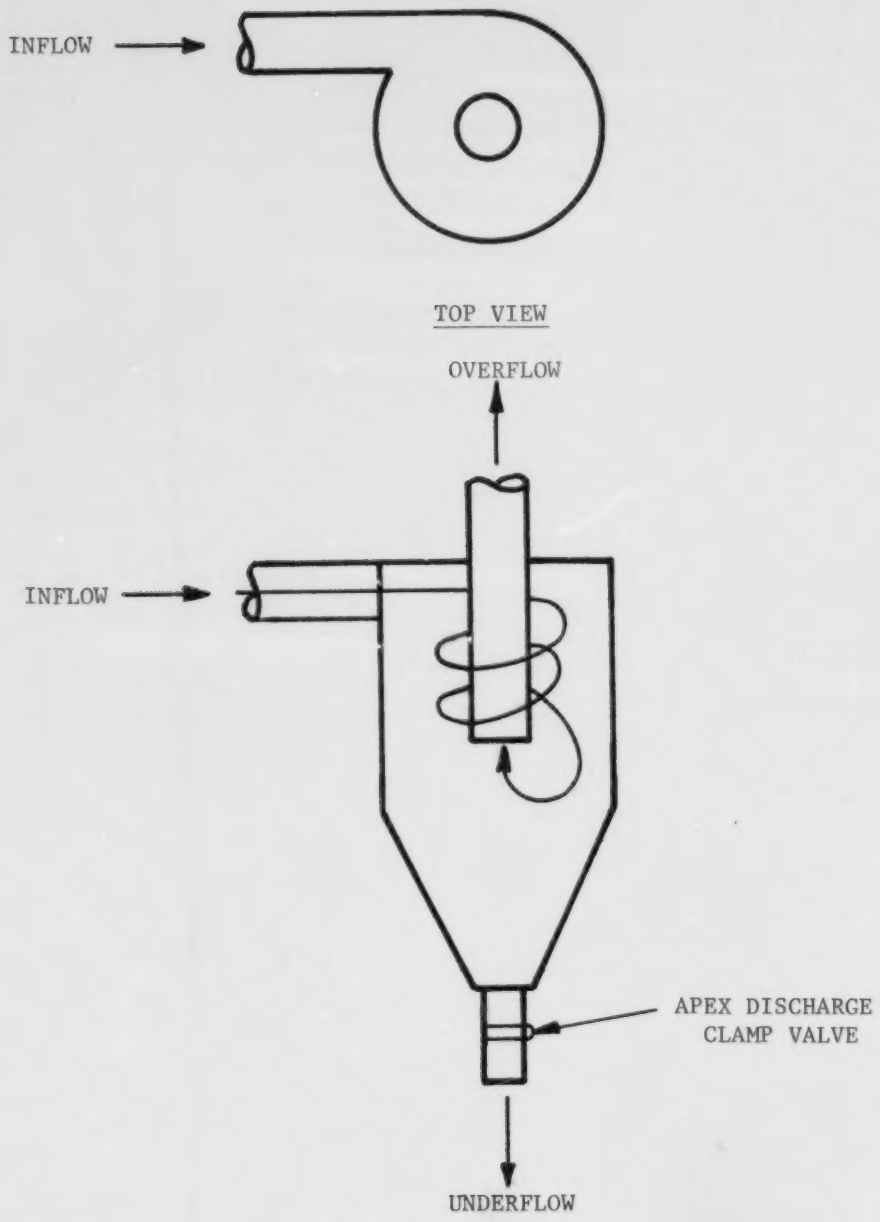


Figure 4. Schematic of hydrocyclone solids/liquid separator.

Water soluble organic - phenol.
Water insoluble organic - polychlorinated biphenyls (PCBs).
Relatively insoluble inorganic - arsenic oxide.

Phenol

The selection of phenol as a soil contaminant for the laboratory testing is well-justified. This chemical is one of the few water-soluble organic compounds that meets the majority of the selection criteria. Phenol is a very hazardous substance that is highly toxic to humans when ingested or absorbed through skin. Fatal doses as low as 1 g have been reported; however, the average fatal dose is 15 g (2). The drinking water standard for phenol (to avoid taste and odor problems) is 0.001 mg/l. This substance is also extremely dangerous to the aquatic environment. The provisional water quality standard for the protection of fish species is 0.01 mg/l. The critical concentration for fish toxicity is 0.1 mg/l, although there are species that can tolerate much higher concentrations (3).

Phenol is ranked extremely high in a ranking system which is used to define potential risks from hazardous materials spills (4). In terms of the total quantity of hazardous chemicals shipped by various means, phenol is ranked 46 (of 257). When ranked according to the overall risk (degree of hazard and possibility of spillage) of spills of soluble hazardous chemicals, phenol ranks first. During a 2.5-year period from January 1971 to June 1973, approximately 293,000 L (77,410 gal) of phenol were spilled in 19 reported incidents. Six additional incidents of spills occurred; however, the quantity spilled was not reported. Three spills resulting from train derailments accounted for 85.3 percent of the total volume spilled during this period (5). These characteristics justify the choice of phenol for testing.

Polychlorinated Biphenyls (PCB)

The major reasons for the selection of PCB as a contaminant for the laboratory testing are the existing soil contamination problems with this material and the hazardous nature of the substance. Unlike many other hazardous chemicals, the probability of spills of PCB during transport are currently quite small since the sale, production, and shipment of PCB was drastically reduced since mid-1971. The majority of all the PCBs manufactured during 45 years of production are still in use, however, primarily in electrical transformers and capacitors, heat transfer systems, and hydraulic systems. When this material is replaced, it is transported to storage and disposal sites. Fortunately, due to stringent government regulation, accidental spills are becoming less frequent; however, there is a significant portion of the total PCB production that remains in the environment (air, water, soil, and sediments). Also, a large fraction of this material is present in dumps and landfills (6). The existence of specific problem areas, such as Chatham County, North Carolina, and other smaller areas throughout the country, provide the justification for laboratory testing of PCBs.

There is little dispute as to the hazardous nature of PCBs. Although it does not exhibit acute toxicity (toxic effects from high level, short-term exposure) it does accumulate in many biological species exhibiting chronic toxicity even at very low concentrations. The chronic or long-term effects of PCB exposure are similar to the chronic effects of DDT exposure. The extremely stable nature of PCBs and their persistence in the environment make this problem much more serious than that encountered with DDT. Unlike DDT, the quantity of PCB present in the environment has not decreased greatly since the initiation of regulations on the production and disposal of these materials (6).

PCBs also meet the other selection criteria for an experimental soil contaminant. This chemical represents a unique group in that it is extremely insoluble and heavier than water. Solubilities of PCB range from 0.24 mg/l for Aroclor 1242 (primarily two, three, or four substituted chlorine atoms) to 0.0027 mg/l for Aroclor 1260 (primarily five, six, and seven substituted chlorine atoms) (6). Therefore, the laboratory approach for testing the feasibility of removing PCB with a soil scrubbing system with water as the solvent had to examine additives such as surfactants to increase PCB solubility. As a result of the extremely low solubilities and the lack of information on how to remove PCB that is bound to organic materials within the soil, this material indisputably meets the "difficulty" selection criterion. PCB also represents an extremely persistent group of chemicals. Its stable nature is one of several properties that made it ideal for use as dielectric and heat transfer fluids. The ability to degrade PCB has been demonstrated in some microbial species, however, the rate at which degradation proceeds is extremely slow. PCB is among the most persistent of all potential organic soil contaminants.

Arsenic

The inclusion of arsenic compounds as soil contaminants for the laboratory testing is to provide information on the feasibility of removing hazardous inorganic materials from soils with a scrubbing system. Arsenic belongs to the chemical group V-A. This group includes typical non-metals (nitrogen and phosphorus), a typical metal (bismuth), and elements that are often referred to as metalloids (arsenic and antimony). Arsenic generally exhibits chemical properties intermediate to the extremes exhibited by other members of this group. Arsenic compounds occur in many forms including halides (e.g., $AsCl_3$, AsF_5), arsenites (e.g., $As_5O_3^{\equiv}$), arsenides (e.g., Zn_3As_2, Mg_3As_2), sulfides (e.g., As_2S_3), oxides (e.g., As_2O_3, As_2O_5), and oxygen acids (e.g., H_3AsO_3) (7). Two common oxidation states of arsenic in solution are As(III) and As(V). The ionic forms and solubility of arsenic present in solutions are highly dependent on oxidation potential (Eh) and pH. Other ions in solution and minerals associated with soil solids influence the solubility and ionic form of As.

Arsenic trioxide (As_2O_3) is the most important arsenic compound in terms of manufacturing technology and is utilized to produce nearly all other arsenic compounds. These compounds include insecticides, weed

killers, rodent poisons, sheep dip, wood preservatives, pharmaceuticals, and hide preservatives. The oxide is also used in the production processes for commercial and ornamental glass, Paris Green, and enamels (7,8). Although there are a large variety of arsenic compounds that could be utilized as potential soil contaminants for the laboratory testing, arsenic trioxide was the most desirable because of its widespread use.

Nearly all compounds containing arsenic are extremely toxic to many animal and plant species. This is verified by the fact that a large number of arsenic compounds are used in an assortment of pesticides and herbicides (7,8). Also, the potential hazard posed by arsenic compounds in general has been evaluated through rankings in terms of the total quantity of materials shipped and the overall risk from a spill. Of the 257 hazardous chemicals considered, arsenic compounds ranked only 221 in the annual quantity shipped. However, when ranked according to the potential risk from spills in aquatic systems, arsenic compounds have an intermediate ranking of 98 (1). There have also been several occurrences of soil contamination problems with arsenic compounds, although these occurrences are not well-publicized in comparison with other contamination problems such as those with PCB.

Solvents

Several classes of additives were considered:

Acids.
Bases.
Polar organics (short chain alcohols).
Oxidizing agents.
Reducing agents.
Surfactants.

Two major considerations for the selection of additives were cost and associated hazards. Extraction of contaminants with an extremely high or low pH solvent would require large quantities of additives. Also, the "clean" soil may not be suitable for return to the spill site without additional treatment. Likewise, additives formulated with extremely toxic components could not be selected.

Solvent for Phenol

Since phenol is a fairly soluble organic (8.2 percent @ 15°C) and is also quite polar, proposed solvent conditions included water alone (neutral pH), water in a pH range from 1.0 to 12.0, methyl alcohol and water, and two aqueous surfactants.

Methyl alcohol was selected as an additive to water since phenol is very soluble in alcohols. Two surfactants (Tween 80 and MYRJ 52 from ICI Inc.) were selected for testing since these materials are manufactured for the purpose of increasing the solubility of organics in water by forming an emulsion.

Solvents for Arsenic

As discussed previously, the solubility of arsenic ions in a soil/water system is influenced by oxidation potential, pH, other ions in solution, and materials associated with soil solids. Therefore, a range in solvent pH, an oxidizing agent (sodium hypochlorite), and a reducing agent (sodium bisulfite) were selected for laboratory testing. At low Eh (oxygen depleted soils), As(III) is the primary form of arsenic in natural soils and the solubility is primarily a function of pH. Below a pH of 8, cationic forms of As(III) predominate, e.g., AsO^{+1}. Various anionic species ($H_2AsO_3^{-2}$) are present at pH values above 9.0. Arsenic (III) oxide (As_2O_3) was selected as the soil contaminant; therefore, a range of solvent pH was considered a viable means of extracting the arsenic from soil. Arsenic can be present in a wide range of oxidation states (-3 to +5), so both a strong oxidizing agent and a strong reducing agent added to water were selected as solvents for laboratory extraction testing.

Solvents for PCBs

In a review of available literature, only one solvent additive was identified as increasing the solubility of PCB in water, namely, a commercially available surfactant called Tween 80.

The solubility of PCB in water varies depending on the number of chlorine atoms in the mixture. For example, the solubility of monochlorobiphenyls range from 1.2 to 5.9 mg/l at 20°C, while the solubility of the decachlorobiphenyl is 0.015 mg/l. The solubility of the decachlorobiphenyl in a 0.1 percent Tween 80 solution is 5.9 mg/l and exceeds 10 mg/l in a 1.0 percent Tween 80 solution.

On the basis of this information, only water and water plus Tween 80 were selected for laboratory testing.

SOIL SELECTION

Two representative soils with differing adsorption capabilities, as well as somewhat variable physical handling potentials, were selected for the laboratory experiments. Since a variety of chemicals were to be evaluated, the broadest range of adsorption potential in terms of organic content was desired. Thus, an organic soil and a non-organic soil were selected.

The nature of the soil structure was also important in the selection of soil types to be evaluated. A soil mass may contain a wide variety of gravels, sands, and clays. The range and proportion of soil types exhibit varying degrees of cohesion between soil particles. The amount of energy required to reduce the soil mass to treatable sizes is a function of the cohesiveness of the soil. A granular sand and gravel soil, being non-cohesive, can be readily separated by sieving or light crushing forces. Silt and clay, because of their cohesive nature, require much more energy for size reduction. Both the organic topsoil sample and inorganic gravel, clay, and silt mixture chosen for testing exhibit cohesive, as well as non-cohesive, tendencies.

Soil Descriptions

Sand with Gravel, Silt and Clay--A naturally occurring sandy material from the Pioneer Pit in Kenosha, Wisconsin was selected as a representative non-organic soil. The clay and silt content was sufficient to provide some cohesive clay lumps, although the material would generally be defined as cohesionless (Figure 5).

Organic Topsoil--The organic soil was manufactured topsoil, produced by the Liesener Topsoil Company of Jackson, Wisconsin. It consisted of moist peat and humus, with little sand. The organic content was 18.4 percent. This material represents a rich, friable, agriculturally excellent topsoil (Figure 6).

Physical and Chemical Characteristics

The physical and chemical characteristics of both soils were evaluated. Physical testing included specific gravity, organic content, unit dry weight, permeability, and gradation. These tests were useful in defining the soils and in establishing correlations with other soil types. Table 1 summarizes the properties of the selected soils.

Figure 7. Inorganic soil for laboratory experiments.

Figure 6. Organic soil for laboratory experiments.

TABLE 1. PROPERTIES OF SOILS SELECTED FOR PRELIMINARY LABORATORY TESTS

Parameter	Topsoil	Sand with gravel, silt, and clay
Physical characteristics		
Specific gravity, g/cm^3	2.21	2.65
Organic content, %	18.40	1%
Natural conditions:		
Moist density, g/cm^3	0.74	2.07
Water content, %	93.40	4.20
Laboratory proctor density:		
Standard method, pcf*	1.00	
Modified method, pcf		2.23
Optimum water content, %	48.70	7.20
Permeability:		
Falling head at natural density condition, cm/sec	1.8×10^{-6}	7.4×10^{-7}
Atterberg limits:		
Liquid limit	74	Non-plastic
Plastic limit	None	Non-plastic
Plasticity index	Non-plastic	Non-plastic
Gradation:		
Percent passing, %		
3/4" sieve, 19.1 mm	100.0	100.0
No. 4 sieve, 4.76 mm	100.0	60.3
No. 40 sieve, 0.420 mm	82.5	22.5
No. 200 sieve, 0.074 mm	56.0	14.9
Chemical characteristics		
Cation exchange capacity, MEQ/100 g	26.0	2.3
pH	6.9	7.9
Conductivity, umho/cm	860.0	400.0
Alkalinity, % $CaCO_3$ by weight	0.61	5.28

*pcf = pounds per cubic foot.

SECTION 5

PRELIMINARY LABORATORY TESTING PROGRAM AND RESULTS

INTRODUCTION

Once the preliminary scrubbing equipment selection and the choices of chemicals and soils for laboratory testing had been made, the actual testing began. The preliminary laboratory testing program had three objectives, namely to:

1. define critical operating variables for potential scrubbing components.

2. develop laboratory procedures that could be used to predict scrubbing efficiency.

3. test three hazardous chemicals representing a wide range of characteristics and potential for being removed by soil scrubbing methods.

The laboratory testing was divided into two main parts. First, equipment testing was performed to establish certain scrubbing system configurations and operating variables. The actual chemical extraction tests were then performed and incorporated much of the information obtained in the equipment testing.

EQUIPMENT TESTING

Prior to beginning the chemical extraction testing, some preliminary equipment testing was needed to define important operating variables for potential scrubbing components. The equipment evaluations centered on three components:

1. Water-knife size reduction and stripping apparatus.
2. Froth-flotation mixing and contact unit.
3. Hydrocyclone liquid-solids separator.

Water Knife Experiments

Testing of the water knives involved determining an effective contact configuration and operational mode including nozzle type and size and water flow-rate and pressure. Initial tests were done with a local subsoil containing large amounts of clay lumps. No chemical contaminants were introduced in this phase of the testing.

Contact Configuration--Several different configurations were tested to determine which one allowed the most effective stripping and lump breaking. Initial tests used the water knives to scour soils laying on a moving, impervious belt. Little lump breaking was accomplished since the high pressure water from the knife propelled the lumps away from the water stream before any breaking up action could take place. Supporting the soils on a screen and even using a secondary screen to sandwich the soil to hold it immobile did not improve the results. It was concluded that the water knife could not function as a lump breaker unless the movement of the lumps was constrained so that they could not move away from the knives. After some discussion of the problem, a tilted, rotary screen was selected as a device which could provide the necessary constraint. A schematic of the water knife and rotary screen assembly is presented in Figure 7 and a photograph of the rotary screen is shown in Figure 8. A U.S. Sieve No. 10 screen (2-mm mesh openings) was selected to retain as much coarse material as possible in the basket for stripping while allowing the fine soil pass-through to be transported to the extraction process. This screen choice represented the smallest mesh that would probably not be subject to plugging problems.

Operational Mode--Various operational modes were tested using about 2.7 Kg (6.0 lb) batches of the local subsoil. The soil was placed into the rotary screen and physically stripped for different time periods at a rotational speed of about 20 rpm. At various time intervals, residual soil weights were recorded and observations were made.

The first tests were performed at a water flow rate of 4.5 l/min (1.2 gpm) and a water pressure of 4.9 Kg/cm^2 (70 psi). The tilted orientation of the rotary screen caused the soil to remain in a small pile near the bottom of the screen. Slow rotation of the screen (10 - 20 rpm) continuously turned the soil mass over to permit the knives to contact more of the soil. In addition, the water knife was moved up and down across the soil pile so that it scoured the entire area of the pile approximately 20 times per minute. As the flow from the water knife contacted the soil, a violent scouring action occurred and much of the loose soil was forced through the screen rapidly. Figure 9 shows that the rapid initial breakdown of the soil reduced the retained volume of the soil by two-thirds during the first two minutes of operation. After this time, the soil reduction rate began to diminish and all that remained in the rotary screen was a small amount of gravel and grayish clay lumps. Effective breakdown of these clay lumps by the water knives continued, but more slowly. A soaking step was found to be helpful in softening the lumps for easier and faster disintegration.

It was concluded from the preliminary lab tests that three cycles are needed for best performance of the water knives on the 2-mm screen:

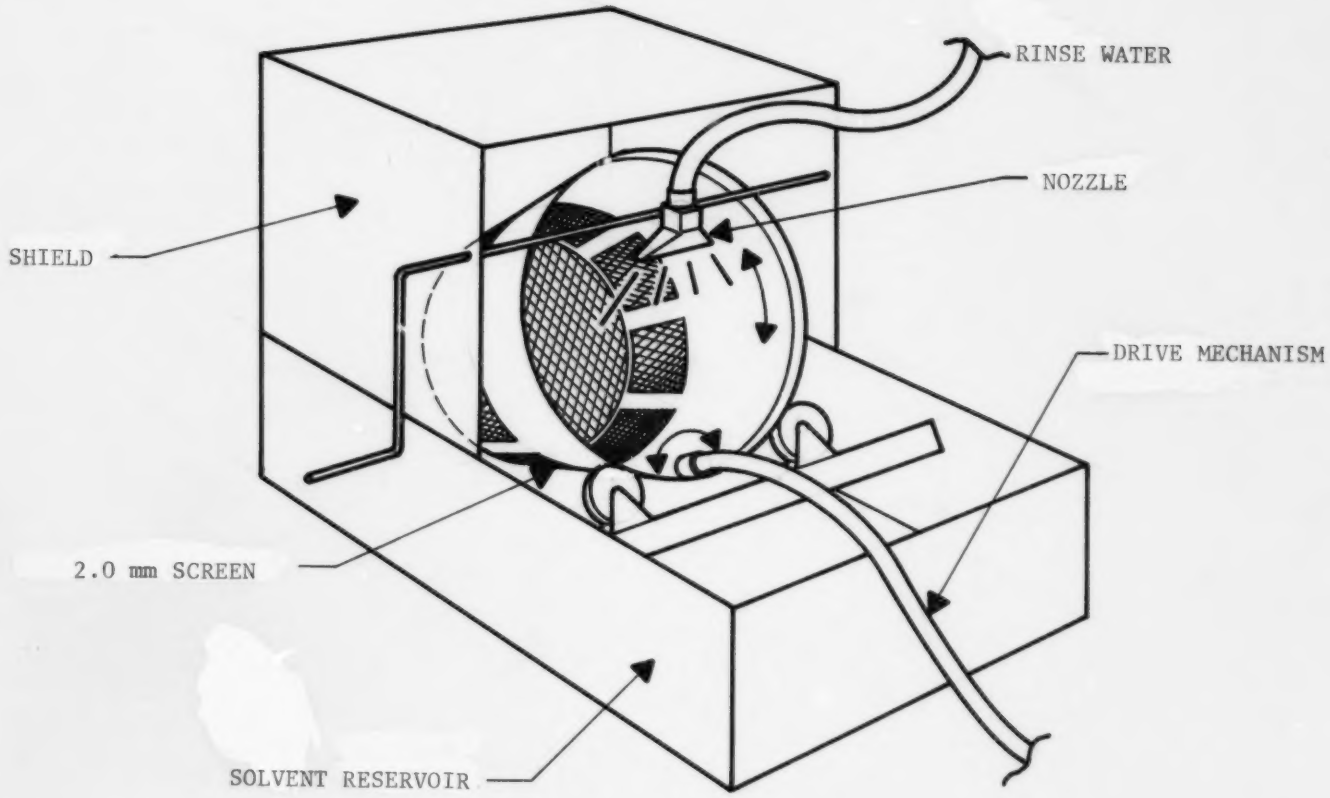


Figure 7. Schematic of water knife testing apparatus.

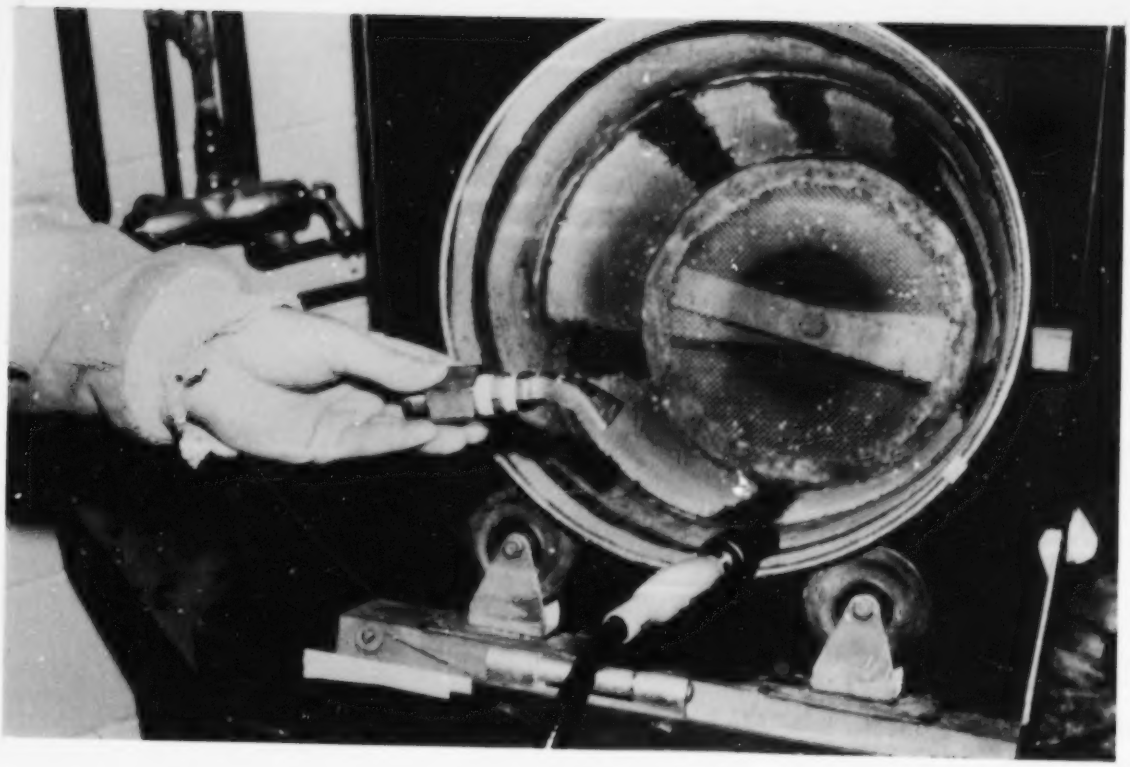


Figure 8. Rotary screen and water knife.

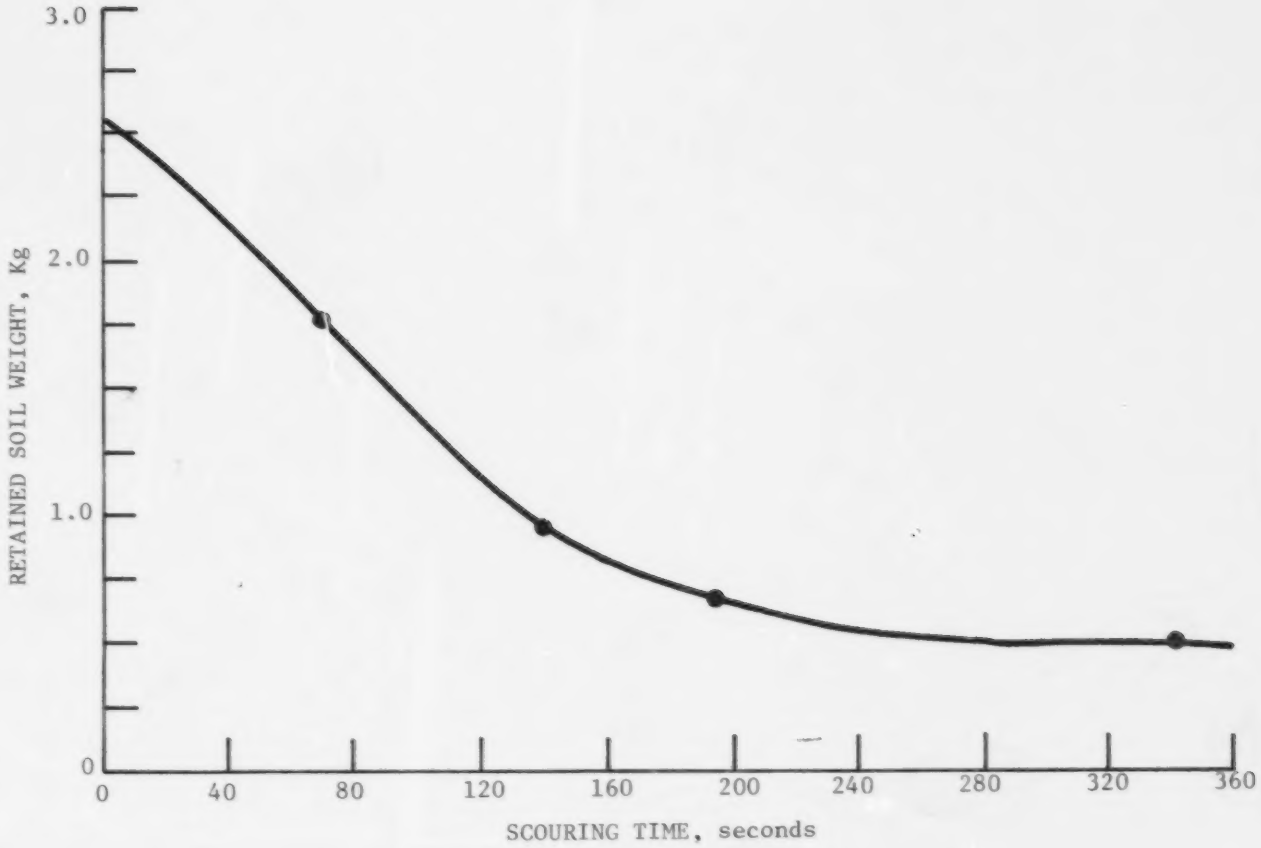


Figure 9. Typical soil breakdown data for preliminary water knife testing.

1. A primary cycle using high pressure fluid recycled from the collection sump. During this period, small soil particles and soil lumps that can be broken down to less than 2 mm pass through the screen.

2. A secondary cycle composed of soaking and of stripping with water knives and spray nozzles.

3. A rinse cycle using clean water at low pressure as a last step before discharge of the retained sand and gravel.

Froth Flotation Unit Testing

One alternative piece of equipment for use as a mixer/contactor during chemical extraction was the available EPA froth flotation unit (13). To determine the feasibility of utilizing the existing mobile froth flotation unit as part of the scrubbing system a laboratory size froth flotation unit was obtained from EPA for use in the testing (Figure 10). Prior to actual chemical extraction testing, preliminary mechanical tests were performed to:

1. Familiarize test personnel with the operation of the unit.

2. Determine the range of unit speed and air flow settings for adequate mixing action.

3. Determine the range of solids concentrations that can be kept in suspension with the unit.

4. Qualitatively evaluate the froth flotation unit for use as a mixing cell in countercurrent extraction.

The mixing action of the unit was first observed using water alone. The pattern of mixing was observed through the Pyrex mixing cell. Different mixing speeds and air flow settings were tested, and it was quite apparent that the parameters were interrelated. Speeds of 1200 to 3100 rpm were tested. When the air flow was too low at a particular mixing speed, the mixing was very turbulent. Increasing the air flow to a certain point resulted in a very smooth mixing action. Once the point of smooth mixing was achieved, increases in air flow had little effect on mixing action. As the froth mixing speed was increased, the air flow necessary to obtain smooth mixing action also increased.

Testing continued using the organic and sand/clay soils with solids concentrations in the range of 10 to 30 percent. The results indicated that, as solids concentrations were increased, higher mixing speeds were required to achieve smooth mixing conditions. Tests conducted at similar concentrations indicated that the same speed and air flow settings were required for

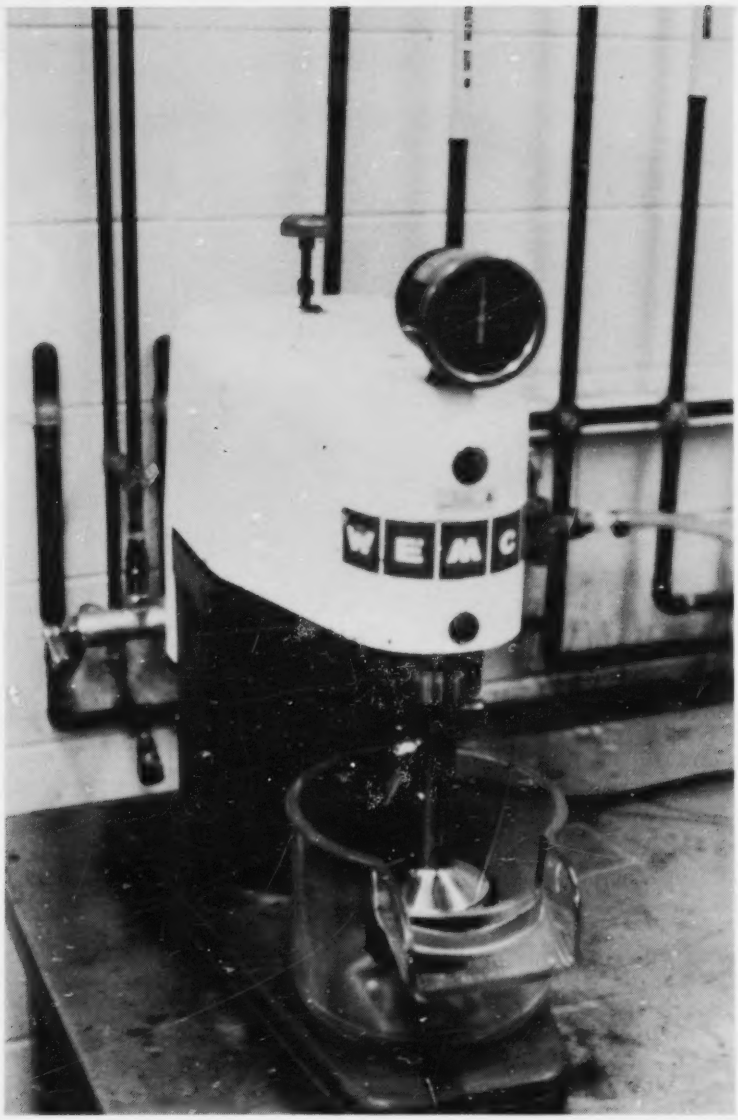


Figure 10. Laboratory froth flotation testing apparatus.

both soils. An air flow of 470 ml/min was sufficient to maintain a smooth mixing action up to an operating speed of 2400 rpm during all of the tests. The quantity of froth produced was generally minimal.

For the organic soil, the best mixing actions were obtained with the operational parameters at the following levels:

Percent solids	Optimum speed (rpm)	Optimum air flow (ml/min)	Comments
11.5	1800 - 2100	470	Little change in mixing when air flow increased to 640 ml/min.
19.1	1900 - 2100	470	When speed increased to 2400 rpm, air flow needed to be increased to 580 ml/min to maintain smooth mixing action.

These results indicate that there were few changes necessary to maintain adequate mixing in this range of solids concentrations. The relationship between air flow and mixing speed observed during the testing with water was also observed when the speed was increased above the optimum to 2400 rpm.

Test results for the sand/clay mixture are summarized as follows:

Percent solids	Speed (rpm)	Air Flow (ml/min)	Comments
18.4	1900 - 2100	470	Air flow of 600 - 640 ml/min required when speed increased to 2400 rpm.
31.0	2700 - 3100	580-610	Some difficulty in keeping all particles in suspension--required balanced adjustment of speed and air flow settings.

Solids concentrations higher than 30 percent were tested with this soil and the froth flotation unit provided an adequate mixing action. However, flow settings seemed more critical and required some adjustments to ensure smooth mixing action at high solids concentrations.

Basically, these results indicate that the froth flotation unit provides sufficient mixing action during chemical extraction of soil particles less than 2 mm in size. Adequate mixing was achieved at solids concentrations up to 30 percent when proper rotational speed and air flow were maintained.

Hydrocyclone Testing

Preliminary equipment evaluations had identified the hydrocyclone as a good candidate for separating the soil particles from the solvent after the extraction steps. In the laboratory testing program, the efficiency of this separation method had to be established for the soil types of interest. After contact with manufacturers, it was determined that accurate and comparable results could not be obtained from a small laboratory-sized unit. The principal problem was the small size of the apex discharge, scarcely larger than the maximum size of the particles in the hydrocyclone feed water (less than 2 mm particles).

Therefore, a full size system, which operated at a flow rate up to 227 l/min (60 gpm) and a pressure drop of 1.4 Kg/cm^2 (20 psi), was obtained for test from Krebs Engineers. According to the manufacturer's specifications, the unit could make a particle separation around 20 - 25 u on a silt/sand mixture with a specific gravity of 2.6. The actual separation efficiency--including the amount of solids entrained in the overflow and the percent solids concentration in the underflow--had to be established prior to the chemical extraction testing. This set of tests was limited to soil and water with no chemical contaminant introduced into the system.

Equipment Setup--A large tank and mixer was utilized to mix the soil (particles less than 2 mm) and water initially and to receive both the underflow and overflow from the hydrocyclone (Figure 11). This setup was required to minimize tank capacity requirements since the hydrocyclone was operated at inflow rates ranging from 95 to 189 l/min (25 to 50 gpm). A large tank mixer was utilized to keep the soil in suspension in the holding tank and a 7.6-cm (3-in.) submersible pump was utilized to feed the hydrocyclone.

The underflow contained the concentrated soil particles whereas the overflow contained only the fine particles, which could not be separated with this hydrocyclone. The apex was a rubber tube that delivered the underflow. The flow ratio of underflow to overflow and the underflow solids concentration could be varied with a hose clamp on the apex.

Test Conditions--Three variables were identified for the laboratory testing of the hydrocyclone, namely:

1. Inflow rate or pressure drop (interrelated variables)
2. Inflow solids concentration
3. Apex setting.

Inflow rates at pump pressures of 0.70, 1.40, 1.80 Kg/cm^2 (10, 20 and 25 psi) were evaluated in the tests. The flow rates associated with these pressure drops varied on the basis of soil type and inflow concentration. Two soil concentrations were utilized for each soil type. The organic soil

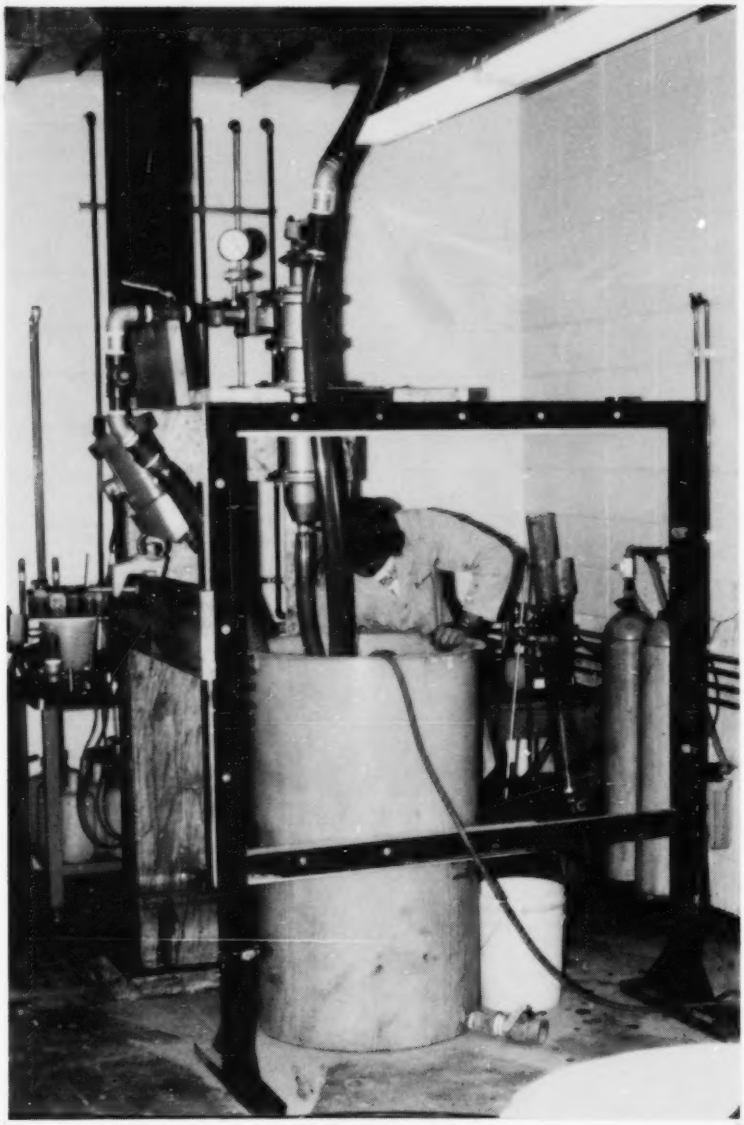


Figure 11. Laboratory hydrocyclone testing apparatus.

was tested at concentrations of approximately 5 and 10 percent dry weight while the inorganic soil was tested at 2.5 and 5 percent solids. A maximum inflow solids concentration of 10 percent was suggested by Krebs Engineers. Krebs Engineers recommended that the appearance of the underflow after it discharged from the apex should be cone-shaped rather than rope-like. Underflow "roping" results from excessive tightening of the hose clamp on the apex. Two extremes of the apex setting were evaluated during the testing:

1. An open setting where no pressure was applied to the apex with the hose clamp.

2. A closed setting where the underflow was still cone-shaped but any additional tightening of the hose clamp results in solids roping.

For each set of test conditions (3 pressure drops x 2 soil types x 2 soil concentrations x 2 apex settings = 24 tests), samples of the inflow, underflow, and overflow were collected and analyzed for total solids. Overflow and underflow rates were also measured for each test condition.

The results indicate that the least sensitive parameters were pressure drop and inflow rate. The following trends were observed with increasing pressure drop or inflow:

1. Underflow, as a percentage of the total flow, decreased.
2. The percentage of the inflow solids in the underflow decreased.
3. The underflow solids concentration decreased.

Although these trends were consistent, the differences observed as a function of pressure drop did not have a significant impact upon test results. Therefore, the data have been summarized by averaging results at the three flow rates.

Table 2 contains the summarized data from the hydrocyclone tests. For the organic soil, the percentage of the total flow as underflow ranged from 4.9 to 18.5 percent and the percentage of the inflow solids concentrated in the underflow ranged from 49.6 to 74.3 percent. Tests conducted with the open apex setting had the highest proportion of inflow solids (63.4 and 74.3 percent) as underflow; however, higher solids concentrations were obtained in the underflow with the closed apex setting.

The inorganic soil results showed similar trends as the organic soil; however, the hydrocyclone was generally more effective in concentrating solids in the underflow in these tests. The percentage of total inflow solids in the underflow ranged from 67.6 to 82.3 percent. Underflow solids concentrations were more than two times higher with the apex closed rather than open.

Particle-size gradation testing was performed for both the inflow and underflow for the inorganic and organic soils. Combined sieve and hydrometer tests were conducted. Testing indicated that the fine fractions were removed from the organic soils in the particle size range of 5 to 300 u.

TABLE 2. SUMMARY OF HYDROCYCLONE TESTING RESULTS

Soil type	Inflow solids concentration, %	Apex setting	Underflow			Overflow		
			Proportion of inflow volume, %	Average proportion of inflow solids,[a] %	Average solids concentration, %	Proportion of inflow volume, %	Average proportion of inflow solids[b] %	Average solids concentration, %
Organic	5.41	Open	16.3	63.4	21.0	83.7	36.6	2.36
Organic	4.87	Closed	4.9	49.6	51.0	95.1	50.4	2.32
Organic	11.56	Open	18.5	74.3	46.5	81.5	25.7	3.42
Organic	9.34	Closed	12.3	65.3	49.8	87.7	34.7	3.70
Inorganic	3.22	Open	18.8	82.3	14.2	81.2	17.7	0.70
Inorganic	2.36	Closed	5.0	67.6	32.3	95.0	32.4	0.77
Inorganic	5.60	Open	16.4	69.6	19.9	83.6	30.4	1.61
Inorganic	4.17	Closed	7.6	68.1	45.4	92.4	35.3	1.67

[a]Calculated as (proportion of inflow volume in underflow, %, x avg. solids conc. in underflow %) (inflow solids conc., %).

[b]Calculated as (proportion of inflow volume in overflow, %, x avg. solids conc. in overflow, %) (inflow solids conc. %).

The majority of change was in the 10 to 200 μ range. The hydrocyclone had no effect on the removal of clay-size particles, namely, those smaller than 5 μ. For the inorganic soil, the particle size gradation removed in the underflow contained a higher percentage of fine particles than the inflow. The fractions of particle gradation removed were in the range of 5 to 1000 μ, especially noticeable in the 10 to 100 μ range. This observation implies that the hydrocyclone removed the coarser fraction from the inorganic silty, fine-to-medium sand soil as expected.

Additional hydrocyclone testing was conducted to determine whether the overflow solids could be effectively removed by an additional hydrocyclone. Tests were conducted with organic soil overflow with a concentration of about 1.7 percent solids and inorganic soil overflow with a concentration of about 1.5 percent solids. Table 3 lists the results from these tests. The majority of the tests were conducted with the apex setting open since the purpose of the tests was to optimize total removal of solids. The results indicated that approximately 25 percent of the solids in the organic overflow and 20 percent of the solids in the inorganic overflow could be removed as underflow. However, the concentration of these underflows was only between 2.0 and 3.8 percent, which indicates that the same hydrocyclone is not an effective means of concentrating the fine soil particles in the underflow. Underflow concentrations as high as 9.0 percent solids were obtained with the closed apex setting, but due to the low rate of underflow with this setting, only 6.5 percent of the inflow solids were removed as underflow. These results show that the same model hydrocyclone cannot be used to clarify the spent solvent used for extraction of contaminants from soil.

Hydrocyclone Simulation Testing

To accomplish a laboratory scale evaluation of the proposed counter-current extraction scheme for the removal of contaminants from fine soil particles (less than about 2 mm in diameter), it was necessary to develop a bench technique to approximate the solids removal achieved with the hydrocyclone. A hydrocyclone could not be used for the chemical testing since the smallest unit readily available for this testing operated through a flow range of 95 - 189 l/min (25 to 50 gpm), much higher than can be efficiently utilized in the lab scale study. Scale down using a smaller hydrocyclone would not be representative of separations obtained in the larger hydrocyclone. Since the 95 - 189 l/min (25 - 50 gpm) flow range was anticipated to be utilized in the full-scale scrubber unit, simulation of this device should give the most valuable results.

Settling tests were tried as a method for simulating solids removal with the hydrocyclone. Initially, samples of the inflow used for the hydrocyclone tests were mixed, poured into a graduated cylinder, and allowed to settle for specified periods of time. Results from the hydrocyclone testing were used to define the relative proportions of underflow and overflow for a given soil type and concentration, and the solids concentrations observed in the overflow and underflow were utilized for comparison purposes. Preliminary tests were conducted assuming both an

TABLE 3. HYDROCYCLONE TEST RESULTS FOR SOLIDS REMOVAL FROM OVERFLOW

Soil type	Inflow solids concentration, %	Inflow rate, gpm	Apex Setting	Underflow			Overflow		
				Proportion of inflow volume, %	Proportion of inflow solids,[a] %	Solids concentration, %	Proportion of inflow volume, %	Proportion of inflow solids,[b] %	Solids concentration, %
Organic	1.74	29	Open	13.8	24.3	3.02	86.2	75.7	1.51
	1.71	39	Open	12.8	25.7	3.36	87.2	74.3	1.43
	1.74	40	Open	12.5	27.6	3.79	87.5	72.4	1.42
	1.72	38.5	Closed	1.2	6.5	9.02	98.8	93.5	1.55
Inorganic	1.52	27.8	Open	13.7	19.1	2.09	86.3	80.9	1.40
	1.51	37.7	Open	12.5	20.6	2.48	87.5	79.4	1.36
	1.51	40.0	Open	12.5	21.7	2.61	87.5	78.3	1.35
	1.50	37.4	Closed	1.1	6.5	8.69	98.9	93.5	1.41

[a]Calculated as (proportion of inflow volume in underflow, %, x avg. solids conc. in underflow %) (inflow solids conc., %).

[b]Calculated as (proportion of inflow volume in overflow, %, x avg. solids conc. in overflow, %) (inflow solids conc. %).

open and closed apex setting with the organic soil. With a 5-percent organic soil inflow and closed apex condition, the underflow volume averaged approximately 5 percent of the total volume for the three flow rates tested with the hydrocyclone. Therefore, after the specified settling time for the simulation tests, 95 percent of the total sample volume in the graduated cylinder was removed using a vacuum trap. This liquid was considered overflow and analyzed for total solids. When simulating the open apex setting, approximately 85 percent of the total sample volume was assumed to be overflow, as determined from the hydrocyclone tests.

Results of the preliminary tests are presented in Table 4. The overflow concentrations were utilized for comparison because of difficulties associated with obtaining a representative sample for total solids analysis of the sludge (underflow) in the bottom of the graduated cylinder. All of the overflow concentrations from the settled samples were close to those obtained from the hydrocyclone. The overflow concentrations for the open apex setting simulation were lower than those for the closed setting since only 85 percent (rather than 95 percent for the closed setting) of the total sample volume was considered overflow. The results from the hydrocyclone testing indicate that the overflow concentrations are not affected significantly by the apex setting.

TABLE 4. COMPARISON OF PRELIMINARY SETTLING TEST RESULTS WITH HYDROCYCLONE OVERFLOW TOTAL SOLIDS CONCENTRATION

Soil type	Apex setting	Settling time, minutes	Overflow concentration, %	
			Settled	Hydrocyclone
Organic	Open	5	2.76	2.36
	Open	20	2.08	2.36
	Closed	5	2.85	2.32
	Closed	20	2.42	2.32

These results indicate that settling was a useful technique for simulating the solids separation achieved with a hydrocyclone. However, the settling technique and times had to be modified so that these could be used in conjunction with countercurrent extraction testing. Additional settling tests were conducted with both the organic and inorganic soils but a large beaker was used for settling the samples which allowed easy removal of the settled solids (underflow). A closed apex setting was assumed for all of the beaker settling tests; and inflow samples, from the hydrocyclone testing, were retained and utilized for these tests. Table 5 lists the overflow concentrations obtained with the settling tests and from the hydrocyclone. The results indicate that short settling times are sufficient to achieve the desired overflow concentration. With the organic soil, a 10-minute settling time provided excellent results for the 5-percent solution,

however, the results indicate that a 5-minute time may be required for the 10-percent solution. With the inorganic soil, the 5-minute settling time provides a good comparison to the hydrocyclone results for both soil concentrations.

The results of the settling tests indicate that, for the soils being tested, settling is a feasible technique for approximating solids removal with the hydrocyclone. The purpose of these tests is not to exactly duplicate the hydrocyclone, but to provide a technique for determining the effects of incompleted soil/solvent separation on the countercurrent extraction system.

TABLE 5. BEAKER SETTLING TEST RESULTS

Soil type	Mixed concentration (%)	Settling time (min.)	Overflow concentration (%)	
			Settled	Hydrocyclone
Organic	5.0	10	2.31	2.32
	5.0	20	1.99	2.32
	10.0	10	2.66	3.69
	10.0	20	2.43	3.69
Inorganic	2.5	5	0.80	0.77
	2.5	10	0.64	0.77
	5.0	5	1.77	1.67
	5.0	10	1.52	1.67

CHEMICAL TESTING

Once many of the mechanical operating parameters were established, chemical testing began. The testing involved several different steps designed to establish test conditions and treatment efficiencies:

1. Column dosing studies, to define the amounts of contaminant to be added to the soil for subsequent laboratory tests.

2. Contaminant distribution tests, to determine the distribution of contaminants according to particle size.

3. Water-knife stripping/soaking tests for particles greater than 2 mm, to determine the ability of this process to strip contaminants from large particles.

4. Extraction tests for particles less than 2 mm, to determine the ability of the countercurrent chemical extraction process to extract chemicals from the soils.

Analytical Techniques

Accepted analytical procedures were utilized for all parameters involved. The specific methods were chosen to provide accurate results with a minimum amount of analytical time. A colorimetric procedure was utilized to quantitate for phenol in order to save analytical time. Although the procedure was straightforward for water samples, soil analysis involved a multiple extraction of phenol into water. The water used in the soil extractions was analyzed and the results summed to obtain the total quantity of phenol in the soil sample. A 2-g sample of soil contaminated with phenol was mixed with 500 ml of clean water and shaken for 15 minutes. The liquid/solid separation was accomplished by centrifuging and the liquid was analyzed for phenol. The soil was resuspended in 500 ml of clean water and the process repeated until the concentration measured in the extract was insignificant compared to the initial concentration. The final result was reported as a summation of the phenol analyzed in each fraction (mg/kg dry soil).

Arsenic analyses were conducted utilizing atomic absorption flame techniques as presented in several sources (9, 10). Soil samples for arsenic analysis were digested with a mixture of hydrochloric and nitric acids. PCB samples were analyzed by a gas chromatography-electron capture detector (11). Hexane was utilized to extract PCB from soil samples for analysis. Standard cleanup procedures were utilized in the analysis.

Column Dosing Studies

The purpose of these tests was to define the amounts of contaminant to be added to the soil for the subsequent laboratory tests. The approach involved simulating a spill condition as much as possible. The liquid contaminants were applied to the surface of the soil columns and the fluid was allowed to drain for 24 hours. In this way, the time factor associated with a spill event was simulated since the contaminant (i.e., pollutant) was primarily retained in the void volume of the soil with less being sorbed on the particles themselves.

Test Methods--A Plexiglas (8.9-cm (3.5-in.) diameter x 15.2-cm (6.0-in.) high) column was packed with soil using a range of soil moisture conditions and dry bulk densities, which simulated natural conditions. A stock solution of contaminant at a volume equal to the soil void volume for the given soil condition was poured onto the column. After 24 hours, the volume of the liquid passing through the column was measured and analyzed for contaminant concentration. The quantity of contaminant entrained by the soil was calculated on a dry soil weight basis. These tests were conducted for both the organic and inorganic soil types.

Stock solutions of contaminant were chosen to simulate conditions expected during a spill. Since technical grade phenol is often shipped as a liquid having a purity of 87 percent, this concentration was used. Arsenic trioxide formed a saturated, aqueous solution (9600 mg/l) within 24 hours, thus simulating the dissolution of solid arsenic oxide after a rainfall.

The PCB concentration occurring during a spill could vary significantly depending upon the situation. A value of about 75,000 mg/l was used for PCB testing.

Column Dosing Results--Phenol was the first of the contaminants tested. Each soil type was dosed under three conditions, namely, concentration of cantaminant, soil water content, and dry bulk soil density. The conditions represent a wide range of natural situations, including high and low soil densities and water contents. Table 6 summarizes the results. For both soil types, the intermediate dry bulk density and lowest water content (tests 2 and 5) resulted in the largest entrainment of phenol. These dosing conditions were then utilized for all further laboratory tests with phenol since they represented worst case conditions. These worst case soil conditions were then used for the dosing studies performed on both arsenic oxide and PCB. The dosing rates determined from these tests are as follows:

Soil type	Arsenic oxide mg As/gm dry soil	PCB mg PCB/gm dry soil
Inorganic	0.75	3.0
Organic	5.00	25.6

Contaminant Distribution Tests

These tests were conducted to determine the distribution of the sorbed contaminants according to soil particle size. Only soils contaminated with phenol and arsenic oxide were used because of hazards associated with excessive handling of soils highly contaminated with PCB.

Test Methods--The methodology for the distribution tests differed for phenol and arsenic because the more volatile phenol could be lost during drying. For phenol, the tests were performed by separating dry soil fractions using a sonic sieving device and then contacting the fractions with phenol stock solution. In order to assure contact of the phenol and the soil fraction, a sample of the fraction was placed on filter paper and then phenol solution was poured over the fraction. It remained in contact with the soil for 18 hours. The soil fractions were then rinsed with water to remove phenol from the void volume and analyzed. For arsenic, contaminated soil from the column tests was dried at 600C, size fractions were separated with the sonic sieving device, and the fractions were then analyzed.

Contaminant Distribution Results--Tables 7 and 8 list the results of the distribution tests for phenol and arsenic, respectively. The results are presented in two ways:

1. Actual contaminant (phenol or arsenic) concentration per unit weight (kg) of dry soil.
2. Percent of total soil contaminant in each size fraction.

Differences of less than 20 percent were found when the fractionated phenol values were summed and compared to the total amount measured on the non-

TABLE 6. COLUMN DOSING TEST RESULTS FOR PHENOL

Test no.	Soil type	Dry bulk density (Kg/m3)	Water[a] content (%)	Dry soil (gm)	Phenol added		Phenol entrained (mg phenol/gm dry soil)
					Volume (ml)	Amount (mg)	
1	Inorganic	2115	7.2	2000	43	37,410	18.7
2	Inorganic	1890	7.2	1788	144	125,280	48.3
3	Inorganic	1890	11.0	1788	76	66,120	7.3
4	Organic	381	93.4	360	465	396,900	64.8
5	Organic	897	25.0	849	354	307,940	452.3
6	Organic	100	48.7	949	55	48,060	63.2

Note: $Kg/m^3 \times 0.062 = lb/ft^3$.

[a]Water content for soils is defined as the weight of water divided by the weight of dry soil (i.e., water content of 93.4 percent means 51.7 gm dry soil per 100 gm wet soil).

TABLE 7. DISTRIBUTION OF PHENOL ON ORGANIC AND INORGANIC SOILS BY PARTICLE SIZE

Soil type	Soil size fraction (mm) Max.	Min.	Percent of soil in size fraction	Measured phenol conc.[a] (mg/kg)	Calculated phenol by size fraction[b] (mg)	Percent total soil phenol in size fraction[c]
Organic	0.074		0.9	7,270	65	0.04
	0.105	0.074	0.8	5,790	46	0.03
	0.177	0.105	3.4	3,100	105	0.06
	0.354	0.177	15.2	7,790	1,183	0.71
	0.595	0.354	22.7	71,130	16,146	9.68
	1.000	0.595	24.1	185,910	44,804	26.84
	2.000	1.000	32.9	317,400	104,425	62.65
	2.000[d]		100.0	208,100	208,100	
Inorganic	0.105		9.5	8,750	840	57.10
	0.354	0.105	15.1	330	50	3.40
	1.000	0.354	45.0	580	261	17.75
	2.000	1.000	30.4	1,050	320	21.75
	2.000[d]		100.0	1,250	1,250	
	12.700	2.000		24,800		

[a]Measured in fraction.

[b]Amount of phenol in a 1.0 Kg total soil sample. Calculated as (percent of soil in size fraction x measured phenol conc. in fraction) ÷ 100 percent.

[c]Calculated by dividing each value of calculated phenol by size fraction, mg, by the total of the chemical for all size fractions, i.e., 166,774 mg for organic soil (sum of "organic" rows 1 through 7 of "calculated phenol" column) and 1,471 mg for inorganic soil (sum of "inorganic" rows 1 through 4 of "calculated phenol" column).

[d]Non-fractioned.

TABLE 8. DISTRIBUTION OF ARSENIC ON ORGANIC AND INORGANIC SOILS BY PARTICLE SIZE

Soil type	Soil size fraction, mm Max.	Min.	Percent of soil in size fraction	Measured arsenic conc.[a] (mg/kg)	Calculated arsenic by size fraction[b] (mg)	Percent of total soil arsenic in size fraction[c]
Organic	0.105		1.7	488	8.3	1.1
	0.177	0.105	3.4	365	12.4	1.6
	0.354	0.177	15.2	277	42.1	5.4
	0.595	0.354	22.7	493	112.0	14.3
	1.000	0.595	24.1	970	234.0	29.8
	2.000	1.000	32.9	1,140	375.0	47.8
	2.000[d]		100.0	806	806.0	100.0
Inorganic	0.105		9.5	420	39.9	22.4
	0.354	0.105	15.1	240	36.2	20.3
	1.000	0.354	45.0	160	72.0	40.3
	2.000	1.000	30.4	100	30.4	17.0
	2.000[d]		100.0	200	200.0	100.0
	12.700	2.000		36		

[a]Measured in fraction.

[b]Amount of arsenic in a 1.0 Kg total soil sample. Calculated as (percent of soil in size fraction x measured arsenic conc. in fraction) ÷ 100 percent.

[c]Calculated by dividing each value of calculated arsenic by size fraction, mg, by the total of the chemical for all size fractions, i.e., 783.8 mg for organic soil (sum of "organic" rows 1 through 6 of "Calculated arsenic" column) and 178.5 mg for the inorganic soil (sum of "inorganic" rows 1 through 4 of "Calculated arsenic" column).

[d]Non-fractioned.

fractionated sample (Table 7) (viz., ((208100-166774)/(208100))x100 = +20% ((1250-1471)/(1250))x100 = -18%). This recovery was quite high considering the natural soil variations and the difficulty of phenol analyses on soils. The comparisons were even better in the case of arsenic (Table 8) (viz., ((806-783.8)/(806))x100 = +3% and ((200-178.5)/(200))x100 = +11%).

Phenol Distribution--The results for the phenol distribution tests onto organic soils indicate that approximately 90 percent of the phenol was sorbed by the larger particle sizes (0.595 to 2 mm). It was hypothesized that this result was caused by a high organic content in these larger size fractions. To further evaluate this, the organic content or loss on ignition (LOI) test was performed on the organic soil. Samples were heated to 550°C for four hours and then reweighed (ASTM Test Designation D-2974). The differing organic content in the coarse and fine fractions was then apparent. When the LOI values and phenol adsorption for different size ranges are presented on the same graph (Figure 12), it can be seen that a direct relationship exists for size ranges between 0.9 mm (U.S. sieve No. 20) and 0.25 mm (U.S. sieve No. 60). This result suggests that woody fiber in the sample sorbed large amounts of phenol. For particles smaller than 0.25 mm, a direct relationship between the organic content and phenol sorption was not observed.

The absence of a direct correlation between organic content and phenol uptake in the fine fraction (<0.25 mm) indicates chemical, as well as physical, difference between the coarse and the finely divided organic fractions. The organic fines are most probably composed of the decomposition products resulting from microbiological attack on plant tissue. These products are commonly termed "humic" or "fulvic" acids and are characterized by large surface-to-mass ratios and an absence of internal structure. The particles are generally the size of clay minerals. By contrast, the woody fibers still retain much of the open structure and porosity of the original plant material. The high phenol sorption in the coarse organic fraction appears to result from the penetration by the phenol into the woody fibers and retention in the internal pore spaces. Conversely, the finely divided organics seem to adsorb in a manner similar to clay slurries. The net result implies that phenol uptake in organic soils may be directly related to the degree of decomposition of the organic materials. Removal of phenol from the internal pore spaces of woody fibers will probably require soaking. Since the phenol appears to have been absorbed by the woody fibers, a wash of the particle surfaces would probably be only partially effective. The conclusion that phenol sorption in organic soils is controlled by the penetration into internal pore spaces of woody fibers also suggests that phenol adsorption would be very sensitive to water content of the fibers. If the internal pore spaces were occupied by water at the time of phenol application, very little sorption would be anticipated immediately. Since either dry or wet conditions may exist in natural soils, the amount of phenol sorption onto larger soil particles at a specific spill site cannot be easily predicted.

Inorganic soil fractions up to 12.7 mm were evaluated to determine phenol adsorption (Table 7, Inorganic). Similar calculations were made with these

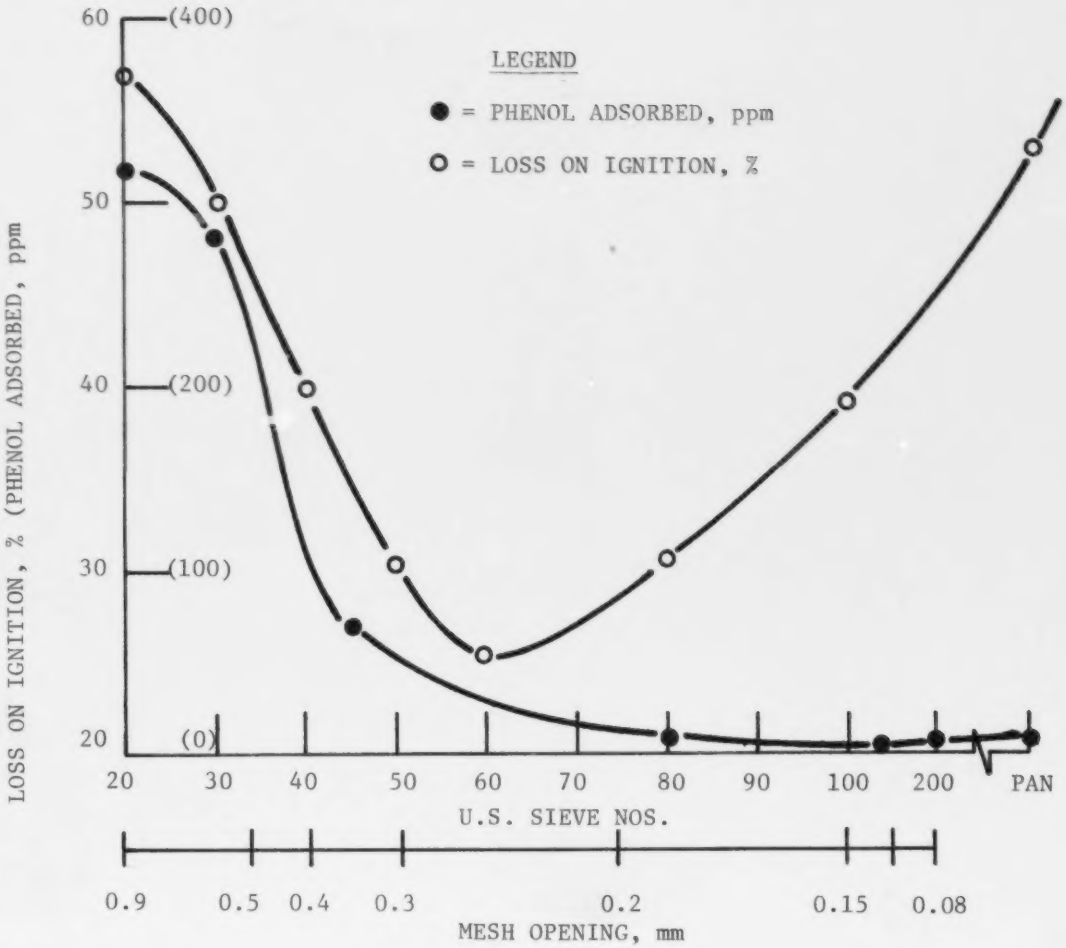


Figure 12. Loss on ignition (LOI) and adsorption of phenol versus soil gradation for an organic soil.

data as had been made with the data from the organic soil tests so the results could be compared. The results indicate that in the particle size range less than 2 mm, approximately 60 percent of the phenol was sorbed by particles less than 0.105 mm (viz., (840/471)x100 = 57%).

The coarse sand and fine gravel material (2 to 12.70 mm) sorbed about three times more phenol on a weight basis than the soil fraction less than 0.105 mm. This result was unexpected because the small particles have a much higher external surface area per unit weight than the gravel. However, the dry, limestone-type gravel found in this soil has a greater total surface area than that calculated solely on the basis of average particle-size diameter. The limestone has a high internal surface area because of pores within the particle itself. These internal pores greatly increase the surface area exposed to phenol in the dosing tests and this condition can account for the higher sorption found during the testing. It should be noted that this sorption was increased because only dry soil was used in the testing. The natural water content of the soil would have filled some of these internal pore spaces and, therefore, decreased the amount of available surface area for chemical adsorption.

Arsenic Distribution--Arsenic distribution on the organic soil (Table 8) indicated that nearly 78 percent of the arsenic was associated with soil particles ranging from 0.595 to 2 mm. The results are similar to those obtained in the phenol testing and can possibly be explained by the retention of arsenic within the pore spaces of the woody fiber present in these size fractions. The smaller soil fractions sorbed approximately the same amount of arsenic per unit weight but contributed differently to the total based on the weight of that soil fraction present in the sample. This is the same trend observed with phenol indicating again that the surface area is not the only phenomenon controlling adsorption.

With the inorganic soil, the smallest size fraction (less than 0.105 mm) had the highest arsenic concentration (420 mg As/kg). When weighted according to soil particle size distribution, this fraction contained approximately 22 percent of the arsenic. The fraction between 0.354 and 1.00 mm contained about 40 percent of the arsenic. However, this result can be explained by recognizing that this size fraction represented 45 percent of the total soil being tested. The higher sorption onto smaller particle sizes is more consistent with expected results, although it is not consistent with the sorption found with phenol. The difference could be caused by the difference in testing methods. For phenol testing, the individual soil fractions were exposed to the phenol and then analyzed. For arsenic, the entire soil mixture was exposed, then fractionated and analyzed. The tech- nique used for phenol would encourage sorption onto the large particles since there was no other sorption media available. Conversely, placing the arsenic onto mixed soils would allow preferential sorption to high external surface area particles of small size and less sorption to internal pores of the gravel.

Water-Knife Stripping/Soaking Tests

The basic equipment operating methodology was established in previous testing. These results indicated that the water-knife apparatus was effective in breaking down clay lumps when a sequence of soaking and water-knife stripping was used.

Chemical tests were then required to establish the efficiency of the water knives in stripping contaminants from large soil particles (>2 mm). Preliminary chemical testing indicated that the submerged (soaking) cycle was also important for effective removal of contaminants sorbed to larger particles.

Test Methods--A 1000-g sample of contaminated soil was placed into the rotary screen and stripped by the water knife with clean water for one minute. This allowed removal of contaminated soil particles that were less than 2 mm in size and also stripped any contaminant present in the void volumes. The percent-removals for treatment-efficiency calculations were based on the amount of contaminant sorbed to the large soil particles measured at this point in the testing. The bucket containing the larger than 2 mm soil particles was then submerged in rinse water for time periods that varied from 15 to 120 minutes. The screen was rotated while it was submerged to encourage solvent/soil contact. Samples were collected at various intervals, rinsed, and analyzed. After 120 minutes, the entire contents of the bucket were rinsed with a low pressure nozzle for one minute, and samples were collected.

Water Knife/Submerged Washing Test Results--Water-knife test results for soils contaminated with phenol, arsenic oxide, and PCB are presented in Table 9. The percent-removals were calculated after the water knife had stripped the contaminant from between the void spaces and removed particles less than 2 mm. Therefore, the results represent actual treatment of the sorbed materials on the particles greater than 2 mm.

Treatment using water-knives and submerged washing was most efficient for phenol (Table 10). The removals were highest for the inorganic soil since almost 98 percent of the phenol was removed from the soil after a 15-min submergence time. Neither arsenic nor PCB was stripped with the same effectiveness even after a 120-min submergence. Removals of phenol from the organic soil were lower, probably because of the stronger affinity of the organic soil for the organic phenol. This trend is not apparent in the arsenic results, which is as expected since arsenic oxide is an inorganic contaminant.

Residual amounts after varying submergence times do indicate continuing removal with time; however, the amount of contaminant removed per unit time becomes less and less. This indicates a decreasing benefit with time and has an impact on the final design considerations. The usefulness of the final low velocity rinse is seen when the residual concentrations at 120 minutes are compared. The final rinse water appears to remove or replace contaminants retained in the washing water that remains entrained in the void volume. A much cleaner product results from the final rinsing.

TABLE 9. WATER-KNIFE TEST AND SUBMERGED WASHING RESULTS FOR SOIL PARTICLES IN THE SIZE RANGE OF 2 mm TO 12.7 mm

Soil type	Test description	Phenol		Arsenic Oxide		PCB	
		Soil conc., mg/kg	Percent removal	Soil conc., mg/kg	Percent removal	Soil conc., mg/kg	Percent removal
Inorganic	Initial (after 1-minute rinse)	3558.0		333.7		14.0	
	15-minute submerged wash and rinse	74.8	97.9	237.2	28.9	11.0	21.4
	30-minute submerged wash and rinse	64.4	98.2	160.0	52.1	21.0	-50.0
	60-minute submerged wash and rinse	42.8	98.8	193.1	42.2	11.0	21.4
	120-minute submerged wash and rinse	32.1	99.1	160.0	52.1	10.0	28.6
	120-minute submerged wash without rinse	149.9	95.8	171.0	48.8	30.0	-114.3
Organic	Initial (after 1-minute rinse)	402,800		6794			
	15-minute submerged wash and rinse	158,400	60.7	3552	47.7		
	30-minute submerged wash and rinse	83,750	79.2	3005	55.8		
	60-minute submerged wash and rinse	56,560	86.0	3097	54.0		
	120-minute submerged wash and rinse	33,930	91.6	2787	59.0		
	120-minute submerged wash without rinse	67,890	83.1	3242	52.3		

TABLE 10. PHENOL DISTRIBUTION IN SOIL SAMPLES USED FOR WATER KNIFE AND SUBMERGED WASHING TESTS.

Soil type	Phenol concentration, units	Soil fractions			
		Complete soil	<2 mm	>2 mm	Soil void spaces
Inorganic	mg/kg[a]	48,300	710	10,770	36,820
	mg/sample	42,700	626	9,520	32,554
Organic	mg/kg[a]	452,200	196,240	18,210	237,750
	mg/sample	254,410	110,400	10,250	133,760

[a] Values listed are mg of phenol in a given soil fraction per kg of complete or non-fractionated dry soil.

Final concentrations of contaminants in the soils varied significantly. Treatment of the phenol-contaminated inorganic soil resulted in the best removals and almost the lowest, post-treatment contaminant concentrations.

Concentrations in the organic soils were much higher, however; the mass of soil involved was considerably less. Only five percent of the organic soil was within the size range of 2 to 12.7 mm treated by the water-knife.

Approximately 50 percent of the arsenic was removed during this processing step for both soil types. Residual arsenic concentrations for the inorganic soils were an order of magnitude less than those on the organic soil, because of the higher initial dosages onto organics and the strong sorption of arsenic oxide to the wood chips and vermiculite present in the organic soil. Residual arsenic concentrations were not significantly changed after 30 min of submergence.

PCB treatment removals were the poorest among all the chemicals tested. The initial concentration was low (only 14 mg/kg) and resultant residual concentrations of approximately 10 mg/kg resulted in only 28 percent removal. The residual concentrations were the lowest for all the chemicals tested. Because of the previously noted trend of even less effective treatment for organic soils, especially with phenol, additional testing of PCB removal on this substrate was judged to be unnecessary.

When evaluating these results, it should be emphasized that the water knife/submerged washing process is performing two functions:

1. Removal of entrained contaminant and separation of contaminated soil particles less than 2 mm from larger soil particles.

2. Removal of contaminant sorbed on the soil particles greater than 2 mm.

Removal efficiencies presented in Table 9 address only the latter functions. If the removals had been calculated based on amounts of contaminant present on the total mass of soil, the percentages would have been much higher because of the relatively high amount of entrained contaminant. Using this overall calculation approach would not have allowed as effective a comparison of actual treatment efficiency among contaminant types. However, the benefits of the water-knife apparatus as a separation device should not be overlooked. Entrained contaminant is transferred from the soil to the water phase using the water-knife. The amounts involved can range from 50 to 75 percent of the contaminant present, which immediately results in a high removal and meets certain goals of the scrubber. Fine soil particles are separated in this step, which also "removes" the contaminant from the surfaces of the larger particles. These processing benefits are crucial to the operation of the unit, although they are not readily apparent when one evaluates only percent removals.

Removal of Entrained Chemicals--The importance of the removal of the contaminant present in the void spaces and sorbed to particles less than 2 mm is further illustrated when the distribution of phenol onto the two soil types is further evaluated (Table 10). This relationship in Table 10 was calculated using the results of the fractionation tests and the amount of phenol dosed onto the soil (see Table 7).

It can be seen in Table 10 that, for both soil types, most of the phenol was entrained in the void spaces. Although a greater percentage of phenol was entrained in the void spaces of the inorganic soil than in the organic soil, 76.2 percent ((36820/48300)x100) versus 52.6 percent ((237750/452200)x100), the entrained quantity of phenol in the organic soil was six times greater than (237750/36820) in the inorganic soil. Since these calculations are based on maximum sorption conditions from the fractionation tests, actual amounts entrained may be even higher. Large particles (greater than 2 mm) in the organic soil contained a large fraction of the phenol (22.3 percent) while this same size fraction contained only four percent of the phenol in the inorganic soil. This is due to the fact that there only was a small fraction of large particles (5.7 percent of the total) present in the organic soil.

CHEMICAL EXTRACTION TESTS

These tests involved contaminant extraction from small soil particles (<2 mm) using a water plus additive solvent system to:

1. Determine the most effective solvent for each contaminant.
2. Establish potential removals of each contaminant using a countercurrent extraction system.

Two types of tests were run: single extraction tests for solvent screening to establish single step removal efficiencies, and multiple extraction tests to measure the improvements that sequential extractions offer on removal efficiency and solvent usage.

Test Methods

For single extraction tests, a Burrell shaker with a 500-ml flask was utilized to mix the contaminated soil and solvent (total volume of 200 ml and dry soil solids concentration of 2.5 to 5.0 percent) for three hours. The mixture was separated by centrifugation and the solvent analyzed for contaminant.

The procedure for multiple extractions was identical to that for the single-step extraction tests except that the contaminated soil was extracted four times instead of once and each aliquot of solvent was recycled in a four-step countercurrent direction (Figure 13). The final or fourth extraction step for the soil was accomplished with clean solvent while the first extraction step used the most contaminated soil and solvent indicative of a countercurrent system operating at steady-state conditions.

The multiple extraction tests were further expanded to simulate the contaminant removal attainable with a full-scale soil scrubber chemical extraction system. Procedures for these tests were similar to those used for the four-step extraction tests; however, the froth flotation unit was used as the mixing cell and settling was used to simulate the soil/solvent separation of a hydrocyclone. The volume of the soil/solvent mixture used in these tests was three liters.

Extraction Test Results

Single Extractions--The results of the single step solvent extractions using different solvent systems are summarized in Table 11. Solvents included water only and water plus additives that appeared suitable for the particular contaminant. In these tests the emphasis was placed on removal into the solvent and no additional rinsing of the soil was performed. It was the purpose of these tests to provide a maximum removal into the solvent by maintaining the complete mix for three hours. The solvent-to-soil ratio was high so that solubility limitations were not encountered and good contact between solids and fluid could be maintained.

Phenol--Removals of phenol from inorganic soils into the solvent phase were most effective. Removals with all of the solvent types were very high and the best extraction occurred with the inorganic soil using water as the solvent. Because of possible experimental errors, the differences among solvents for this soil system were probably not significant. The inherent advantages of using water alone in a soil system (e.g., cost, operational simplicity, lower corrosion potential) make this the preferred solvent.

Phenol removals from the organic soil were not so high but large quantities of phenol were also extracted into all of the solvents tested. In this soil, the most effective solvent system was water with sodium hydroxide added to maintain a pH of 11. However, the handling difficulties associated with this rather alkaline solvent system could be a major disadvantage. Water alone, with a removal efficiency not significantly less than the alkaline solvent, would probably be a suitable choice for the organic soils also.

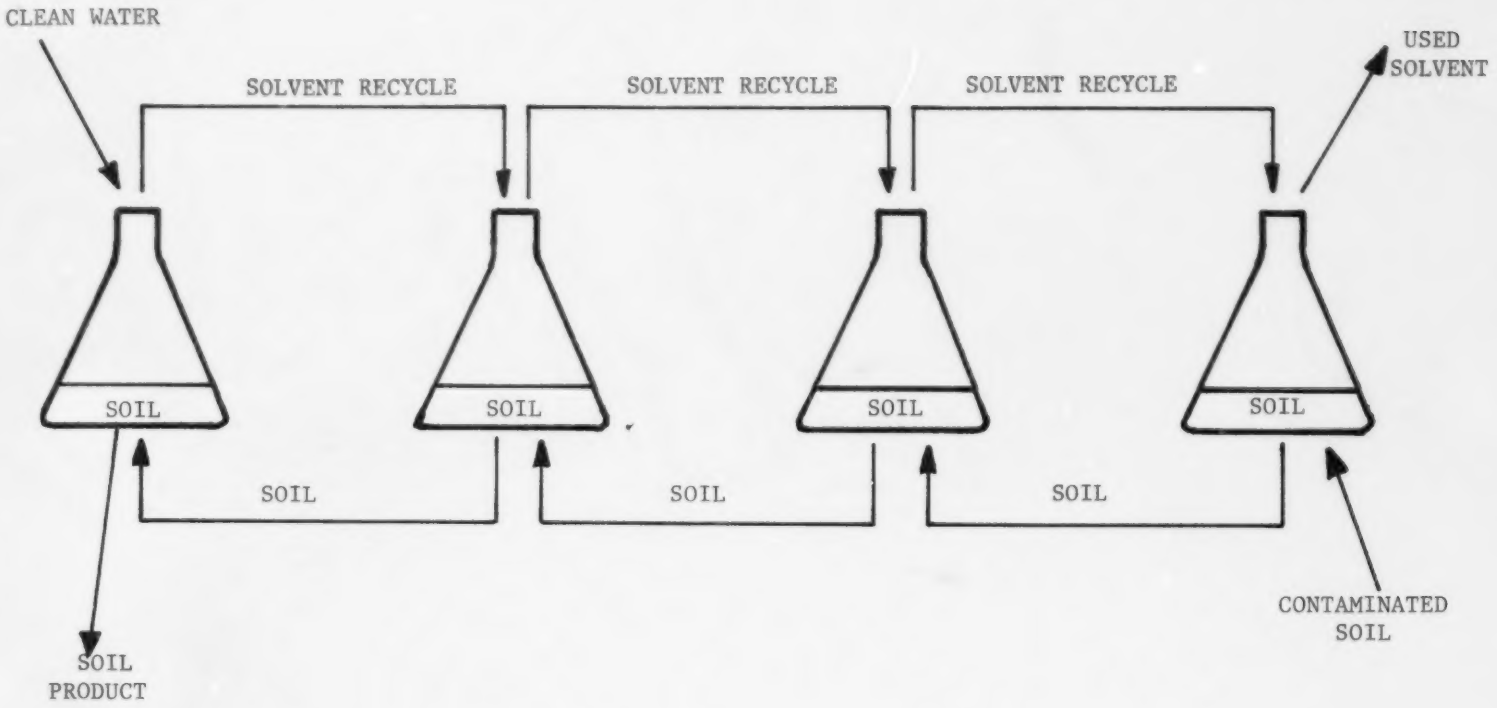


Figure 13. Soil and solvent movement during shaker tests with solvent recycle.

TABLE 11. SINGLE EXTRACTION TEST RESULTS

Contaminant	Soil type	Solvent type	Initial pH	Supernatant contaminant concentration, mg/l	Percent removal	Soil residual contaminant concentration, mg/g
Phenol[a]	Inorganic	Water + H_2SO_4	1.0	1,120	92.8	3.48
		Water + H_2SO_4	3.0	1,100	91.1	4.30
		Water + H_2SO_4	5.0	1,100	91.1	4.30
		Water + NaOH	11.0	1,060	87.8	5.89
		5% MeOH	6.7	1,100	91.1	4.30
		1% Tween 80	6.4	1,120	92.8	3.48
		1% MYRJ 52	6.3	1,180	97.8	1.06
		Water	6.9	1,190	98.6	0.68
Phenol[b]	Organic	Water + H_2SO_4	1.0	16,300	72.1	126.2
		Water + H_2SO_4	3.0	18,000	79.6	92.3
		Water + H_2SO_4	5.0	18,600	82.3	80.1
		Water + NaOH	11.0	20,000	88.4	52.5
		5% MeOH	7.1	18,600	82.3	92.3
		1% Tween 80	7.1	16,200	71.6	128.5
		1% MYRJ 52	7.1	15,300	67.7	146.1
		Water	7.1	17,600	77.8	100.4
Arsenic[c]	Inorganic	Water + H_2SO_4	1.0	32	85.3	0.11
		Water + NaOH	10.0	16	42.7	0.43
		Water + NaOH	12.0	18	48.0	0.39
		7.5% NaHSO		23	61.3	0.29
		5.0% NaCl		22	58.7	0.31
		Water		16	42.7	0.43
Arsenic[d]	Organic	Water + H_2SO_4	1.0	425	85.0	0.75
		Water + NaOH	10.0	310	62.0	1.90
		Water + NaOH	12.0	405	81.0	0.95
		7.5% NaHSO		405	81.0	0.95
		5.0% NaOCl		285	57.0	2.15
		Water		375	75.0	1.25
PCB[e]	Inorganic	0.1% Tween 80		61	20.8	2.38
		1.0% Tween 80		110	37.5	1.88
		Water		72	24.6	2.66
PCB[f]	Organic	0.1% Tween 80		850	20.8	20.3
		1.0% Tween 80		366	23.8	19.5
		Water		418	48.3	13.2

[a]Initial soil dose was 48.3 mg phenol/g dry inorganic soil.
[b]Initial soil dose was 452.3 mg phenol/g dry organic soil.
[c]Initial soil dose was 0.75 mg As/g dry inorganic soil.
[d]Initial soil dose was 5.0 mg As/g dry organic soil.
[e]Initial soil dose was 3.0 mg PCB/g dry inorganic soil.
[f]Initial soil dose was 25.6 mg PCB/g dry organic soil.

Arsenic--The maximum removal of arsenic into the solvent phase was less efficient than for phenol when inorganic soils were extracted (85.3 percent as compared to 98.6 percent) but approached the extraction efficiency of phenol on the organic soils (85 percent as compared to 88.4 percent).

Arsenic removal from organic soils was significantly affected by the type of solvent used; water with sulfuric acid appeared to be the best solvent (85-percent removal at pH 1.0) whereas water alone or water plus NaOH removed less than half of the arsenic. When acid is used as a solvent in the full scale system, the equipment used for chemical extraction must be constructed with suitable corrosion-resistant materials. Care is also required in the handling and use of the acid. When acid is not used, the next best solvent for the inorganic soils is the sodium bisulfate (7.5 percent $NaHSO_4$) with a 61.3-percent removal.

With the organic soils, the differences among solvents were not so dramatic; and water alone, as well as water plus NaOH or $NaHSO_4$, produced results almost as good as the water plus sulfuric acid.

Another concern with the arsenic results was the low concentrations of this material measured in the solvent. The solubility of arsenic in the solvents tested is many times higher than the levels obtained during any of the extraction tests. This result implies, at best, the need for large volumes of clean solvent--and possibly longer contact times to better approach equilibrium--to reduce residual soil concentrations to lower levels. The result also raises questions about the extent of further reduction in soil arsenic levels with multiple extractions. With lower residual soil concentrations, solvent volume requirements may be even higher. It was also significant that the concentrations measured in the different solvents did not vary greatly. These relatively small differences are important, however, when comparing extraction efficiency by solvent type. Because of the relatively small amount of arsenic in the soil system, the measured differences in solvent concentrations do result in large differences in removal efficiencies.

Problems occurred with the analysis of arsenic contaminated soils, particularly for the inorganic soils. A strongly acidic solution was required to obtain total digestion and reproducible results. Digestion of soils was attempted with nitric acid alone, mixed nitric and hydrochloric acids, and nitric acid with hydrogen peroxide.

Use of an extracting mixture of nitric and hydrochloric acid and quantitation by atomic absorption spectroscopy yielded reproducible arsenic analyses. However, the difficulties in analyses and the requirement for such a rigorous digestion illustrate the potential difficulties associated with complete removal of arsenic into a more moderate solvent system, which could be used in the soil scrubber. Even a mixture of water and acid at pH 1, which gave the best comparative removal, does not provide the optimal type of extractant that is needed for complete arsenic removal.

PCB--PCB removal into the three solvent-types tested was quite low. A maximum removal of 48 percent was noted for the inorganic soil. It should be observed that the PCB concentration in the supernatant greatly exceeded the solubility of PCB in any of the solvent mixtures. This indicates that the shaker tests were actually performing a physical separation rather than a purely solvent extraction. PCB that had been entrained in the soil was removed and actually formed a third phase, which was noted by the laboratory analyst. Because the procedure used in the laboratory testing does not provide the longer times necessary for soil/chemical bonding, the test results are difficult to apply to remedial-action type situations, which are probably those situations for which scrubbing of PCB from soils is most needed. In those situations, much of the entrained PCBs would be gone and the remaining contaminant would be more tightly bound to the soil itself. Depending upon the type of soil and many other factors, the remaining PCB concentration may be either high or low. Lab-scale treatment of PCB in a remedial-action-type situation would have to be modified to accurately predict the impact of the critical time factor on removal efficiencies.

Multiple Extractions--Phenol was selected for establishment and demonstration of the efficiency of multiple extractions and its effect on solvent usage. Arsenic was not used for the demonstration because it appeared that further extractions would probably not be effective in reducing the soil arsenic levels substantially because of the small amount of contaminant that the solvent was able to remove in a single extraction and the awareness of the tight bonding of the arsenic to the soil, as shown by the difficulty in removing arsenic from the soil by acids for analysis. PCB was not used for the demonstration because of its low efficiencies of initial removal. Its hazards also detracted from using it for this initial demonstration.

The first test run with phenol was a quick check to demonstrate the potential for solvent reuse. Two aliquots of soil were contaminated with phenol and extracted; the same volume of water was used for each extraction. In one experiment, an aliquot of soil (# S-1) was washed twice with clean water (# W-0) and the washings (# W-1 and W-2) were saved. In the second experiment, a fresh aquilot of soil (# S-2) was first washed with used wash water (# W-2) from the second washing of the first aliquot of soil (# S-1) then rewashed with clean water (# W-0). The results indicate that used solvent could remove nearly as much phenol from contaminated soil as clean solvent, so solubility limitations did not impede removals in this case. The more detailed four-step, countercurrent extraction tests were then conducted.

The results show that, for phenol, multiple extractions were far more effective than a single extraction in removing the chemical from the soil (Table 12). Multiple extractions continued to remove phenol at high efficiencies so that after the fourth extraction the percent of initial phenol retained by the soil had been reduced to a small fraction of a percent. A log-normal plot of retained phenol versus number of extractions indicates that the efficiency of extraction had not yet diminished significantly after four extractions and that further extractions could be

TABLE 12. SUMMARY OF PHENOL EXTRACTION EFFICIENCY FOR COUNTERCURRENT EXTRACTIONS.

Soil type	Identification of sequential batch extractions (a, b)		Soil phenol			Solvent phenol		
	Soil	Solvent	mg/kg	mg/sample	Percent retained[c]	mg/l	mg/sample	Percent removed[d] (cumulative)
				Shaker tests and centrifugation				
Inorganic	1	4	1106 (1050)[e]	11.06 (10.50)	2.29 (2.17)	2425 (2400)	485 (480)	100.4 (99.4)
	2	3	286	2.86	0.59	135	27	5.6
	3	2	89 (81)	0.89 (0.81)	0.18 (0.17)	25	5.0	1.04
	4	1	29 (30)	0.29 (0.30)	0.06 (0.06)	5.9 (4.2)	1.18 (0.84)	0.24 (0.17)
				Froth flotation and settling				
Inorganic	1	4	7,620	873.3	12.05	2,750	7631	105.3
	2	3	954	114.5	1.58	295	818	11.3
	3	2	350	39.0	0.54	75	208	2.9
	4	1	79	8.3	0.11	29	80	1.1
Organic	1	4	79,170	21771.8	16.05	50,000	132,000	97.3
	2	3	16,340	3627.5	2.67	11,000	29,040	21.4
	3	2	7,180	1306.8	0.96	2,850	7,524	5.5
	4	1	2,560	542.7	0.40	2,000	5,280	3.9

[a] In each set of 4 extractions, the most contaminated soil (#1) was first treated with the most contaminated solvent (#4). Centrifuged (or settled) soil #1 was then designated as soil #2 and treated with the solvent (#3) separated from the next batch (soil #3, solvent #2) and so on until in the last batch operation, the soil (#4) that had been sequentially washed with solvents #'s 4, 3, and 2 was then admixed with neat solvent (#1).

[b] The initial phenol dosing for the 3 batch sequences were: inorganic shaker = 485mg/100g dry soil; inorganic froth = 7.25g/115g dry soil; organic/froth = 135g/275g dry soil. The corresponding solvent/dry soil ratios are: 200ml/100g; 2.75L/115g; 2.65L/275g.

[c] Percent of dosed phenol remaining on soil.

[d] Percent of dosed phenol removed from soil to solvent.

[e] Values in parenthesis are from duplicate extraction series.

expected to further reduce the phenol content from the soil (Figure 14).

Reduction in soil phenol resulted in a residual soil product concentration of about 30 mg/Kg after four extractions using the shaker test and centrifugation.

The phenol present in the solvent increased progressively with the number of extractions, however, the majority of the phenol was removed in the first stage by contacting the contaminated soil with previously used solvent. The incremental increases in phenol concentration were much lower in the subsequent soil extractions. Fresh solvent was used in the last (4th) extraction.

When these results were further evaluated, it was determined that the removal of phenol after three extractions with recycled solvent was equivalent to the removal provided by two clean water extractions. Four extractions provided even better removals than two clean water extractions with half the water requirement.

The use of froth flotation and settling as an extraction apparatus to establish the impact of incomplete soil/solvent separation as would occur with the use of hydrocyclones resulted in a similar trend of reduction of chemical level in the soil, but with somewhat less efficiency. Removals were more efficient from inorganic soils than from organic soils, as the previous single extraction test data had predicted (Table 11).

However, the final concentrations of phenol in the soil products are much different for the two soil types (79 mg/Kg for the inorganic soil and 2560 mg/Kg for the organic soil) due to three factors:

1. The organic soil was dosed with approximately ten times more phenol per gram of dry soil than the inorganic soil.

2. The concentration of dry soil in the froth unit for the organic soil was 10 percent versus 5 percent for the inorganic; therefore, there was less solvent per gram of dry organic soil.

3. The organic soil retained the phenol more tightly because of the nature of the soil.

An additional factor that should be considered in examining the results is the loss of a portion of the soil in the overflow (simulated). For the inorganic soil, approximately 25 to 30 percent of the soil dry weight was lost in the simulated overflow during the four-step extraction process. Losses of up to 40 percent were observed in the overflow during the organic soil extractions. Although settling was utilized to simulate soil/solvent separation, these soil-loss values should be indicative of the expected soil loss when hydrocyclones are actually used in separation/processing.

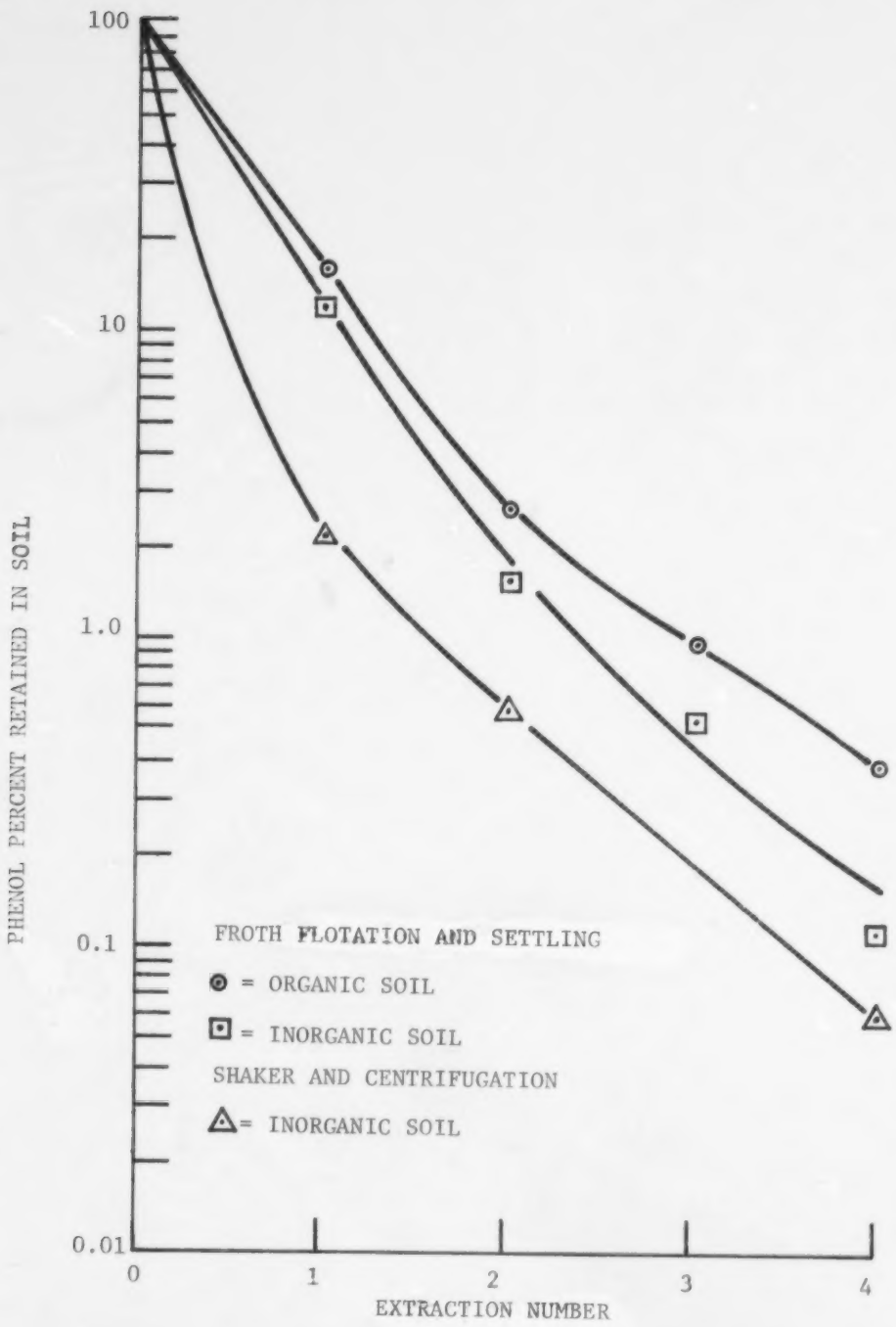


Figure 14. Soil phenol reduction as a function of number of extractions using two different extraction methods.

SECTION 6

IMPLICATIONS OF THE PRELIMINARY LABORATORY TESTING PROGRAM ON SYSTEM DESIGN AND SOIL TREATMENT

INTRODUCTION

The information obtained from the preliminary evaluation and the laboratory testing allowed an initial evaluation of the soil scrubbing concept and provided a basis for the design. Since initial laboratory testing was limited to three different chemicals, broad generalizations regarding the scrubber's range of application were difficult to establish. Instead, the results were considered indicators of the effectiveness and usefulness of soil scrubbing on the particular chemicals tested and the classes they represent. The same concept holds true when extrapolating the impact of different soil types on the scrubber unit. Implications on system design based on the equipment review and the laboratory testing are presented below, followed by implications from the chemical testing.

IMPLICATIONS FROM EQUIPMENT TESTING

Water-Knife Stripping

Physical stripping of both free contaminant and that bound to soil particles using a water-knife system was found to be effective. Breaking down small, cohesive, clay lumps can be accomplished using water knives in conjunction with a soaking cycle.

The most effective configuration was found to be an internally water-knife washed rotary screen unit which passed particles less than 2 mm in size and provided the action to flush (strip) contaminating chemicals from the particles greater than 2 mm in diameter that were retained in the screen chamber. This system allowed the retained soil to be confined in a pocket so that the force of the water knives could be fully utilized. A three-step operation, which included an initial stripping with the water knives to remove fines and entrained contaminant, a submergence step for lump softening and treatment, and a final rinse, was found to be effective. Recycle of water for the first high pressure stripping appeared desirable to reduce water requirements in the system. The final rinse utilized a lower pressure, clean water stream to remove contaminated water from the soil surfaces.

Froth-Flotation Mixing and Contact

The froth-flotation system provided smooth, efficient mixing using a combined mechanical- and air-mix system. The two mechanisms were interrelated with optimum settings established by soil type and solids concentrations.

Solutions containing 30-(or greater) percent solids were effectively mixed with this system. The amount of froth generated in clean soils was minimal. The process limitations of applying froth flotation to the scrubbing system, however, include the added difficulty that would be encountered in controlling emissions from volatile contaminants and the possible foaming problems when surfactants are used as additives for chemical extraction.

Hydrocyclone Liquid/Solids Separation

Hydrocyclone testing also had a direct impact on the scrubber evaluation. The equipment operation was quite simple, and only a manual apex adjustment was needed to control solids concentrations in the underflow.

With a closed or tight apex setting, the solids concentration in the underflow ranged from approximately 30 to 50 percent. This concentration should be acceptable for discharge of cleaned soils, possibly with some auxiliary drainage on sand beds.

Mounting hydrocyclones above the mixing tanks of the modified oily beach sand cleaner was no problem and the units are capable of operation over a relatively wide flow range. Another advantage is that changes in the flow rate do not have adverse impacts on the solids concentration in the underflow. The major disadvantage of the hydrocyclone is the amount of solids that is entrained in the overflow of the unit. Solid recoveries of 70 percent were measured; however, 30 percent of the solids passed out of the system with the overflow. The solids concentrations in the stream ranged from 0.7 to 3.7 percent. Treatment of this stream with a similarly sized hydrocyclone was ineffective. It is likely that an additional, more efficient hydrocyclone or that chemically assisted gravity separation will be needed prior to any additional treatment for solvent recycle.

IMPLICATIONS FROM CHEMICAL TESTING

The results of the different tests performed during the preliminary laboratory studies had an impact on the design and operation of the soil scrubber. An evaluation of their effects are presented in the following section.

The chemical test results were somewhat inconclusive since a defined system endpoint has not been established for the chemicals tested. The most effective treatment, in terms of percent removed, was found for phenol. Neither arsenic oxide nor PCB was scrubbed with as high a removal efficiency. In all cases, the residual soil concentrations were reduced; but, without established, acceptable concentration limits, the results are difficult to evaluate.

Contaminant Distribution

Varying sorption with particle sizes was expected; however, the results obtained during the testing were not so straightforward as anticipated. The larger soil particles in both the organic and inorganic soil sorbed a greater fraction of contaminant than would be predicted based on nominal

surface area. This result can be partly explained by the open structure of the coarse, woody fibers in the organic soil and by the dryness and pore structure of the limestone gravel in the inorganic soil.

On the basis of these experiments it does not appear fully justified to assume that small particles will adsorb more contaminant per unit weight than large particles. A number of variables besides particle size appear to impact how much contaminant sorbs to a particular soil including:

1. initial moisture content of the soil
2. internal structure of the soil particle
3. nature of the soil material
4. manner in which the contaminant contacts the soil
5. duration of contact time between contaminant and soil.

It is difficult to predict soil/chemical interactions, which emphasized the need to make the soil scrubber as flexible as possible.

Effectively treating soils by concentrating on a predetermined soil fraction is also difficult. With the extreme variations of soil gradation and of chemical sorption to different soil materials, an inflexible approach would significantly limit the scrubber's effectiveness and usefulness.

Contaminant distribution information, nonetheless, is still very useful because the data may be applied to estimate the overall scrubber effectiveness when the contaminant sorption by particle size and the particle size distribution of the soil are known. Both large rocks and boulders and extremely fine clays will escape treatment because of system limitations. Knowing the fractional distribution of particles between these two limits permits calculation of a theoretical system efficiency.

Water-Knife Stripping

The submergence step, which has been found to be necessary for both softening lumps and cleansing of the larger particles, was studied. A submergance time of 15 min provided good removal without greatly slowing down the processing rate. However, the differences in soil and contaminant types emphasize the need for flexibility in system operation. The three-step approach, i.e., initial stripping, soaking, and rinsing, was effective; however, the final rinse prior to discharge had to be performed with low-velocity spray jets for the most efficient removal of the contaminant.

Chemical Extraction

The single solvent extraction tests provided a way to compare solvents and to establish preliminary removal efficiency ranges for soil treatment. The contaminant tested that had the best results in these tests (phenol) was further tested in a multiple extraction scheme, which simulated the four-step extraction system proposed for the prototype soil scrubber. Multiple extractions resulted in continued, efficient removal of phenol from soil to low residual values. In these tests, solvent reuse in a countercurrent scheme was shown to be an effective approach.

Other Considerations for Chemical Treatment

Residual Soil Contaminant Levels--A second and possibly more critical factor that must be further addressed involves the residual contaminant levels remaining in soil after treatment. This factor is of particular importance when one evaluates the preliminary laboratory results. Acceptable soil concentration limits are not always available, so it is difficult to determine whether the treatment has been "successful." Calculation of percent-removal is one way to begin the evaluation, but these numbers can be misleading since different initial amounts of material were used. Therefore, it was necessary to reassess the results from a slightly different point of view.

It became apparent that the soil scrubber system itself might be able to establish an acceptable upper limit of residual contaminant concentrations in the soil. Since the scrubber is designed to remove materials into a water solvent under forced conditions, the residual remaining on the soil should have limited mobility in the natural environment. It is expected that the material left sorbed to the soil after the sequential extractions will be very tightly held and have minimal environmental impact. The release of the chemical may continue but at a rate so extremely low that there is no significant environmental danger. If concern still remains regarding the impact of a specific chemical, disposal to a sanitary landfill or other site with more controlled access may be an acceptable compromise.

The post-processing disposal option concept can be further evaluated by considering the three chemicals tested in the laboratory study. Phenol removals after step extraction were high (>99 percent for both organic and inorganic soils) with lower residual concentrations on the inorganic soil. These results were anticipated because of the organic-chemical-to-organic-soil attractions. Since the phenol was not so effectively desorbed from the organic soil, or from the inorganic soil it is apparently not so mobile, i.e., it is more tightly held. This observation appears to confirm the hypothesis that the chemical that is removable is scrubbed and that which remains may be quite tightly bound to the soil. Using this concept, the natural attenuation or treatment capacity of the soil then works in favor of the treatment approach rather than against it.

The same concept is more graphically illustrated when considering the other two chemicals tested, arsenic oxide and PCB. Arsenic has a strong affinity for the fine inorganic soil particles, probably due to an ion-exchange type mechanism. It is also held quite tightly to the organic soil. The relatively high residual concentrations of arsenic after treatment and the relatively low arsenic concentrations in the solvent confirm the strength of the soil/arsenic attraction. Another indication of this interaction can be found when considering the rigorous analytical procedure needed for total arsenic analyses. The soil sample was completely digested in a mixture of nitric and hydrochloric acid before a consistent arsenic measurement could be obtained. If arsenic is so difficult to remove during analysis, it is not likely to be mobile in the natural environment. Studies of the natural attenuation properties of soils tend to confirm this result.

Multiple extractions of soil contaminated with arsenic have not been run; but it is expected that, unlike phenol, the extraction efficiency will decrease substantially with each successive extraction. The probable effect will be that, after only a few extractions, very little additional arsenic will be drawn into the solvent and further treatment by soil scrubbing will be marginally useful in effectively reducing soil arsenic levels. If additional arsenic cannot be forced out of the soil by rigorous stripping and extraction, it should be quite immobile in the natural environment.

Treatment of PCB using the scrubber approach provides the most difficult challenge for effective treatment. These materials have an extremely limited water solubility and a strong affinity for soils. Laboratory tests indicated that some PCB was removed into the water phase but much of what was being processed remained in the soil. However, the initial sorbed amounts of PCB were quite low since the lab approach, simulating a spill situation, allowed only a 24-hour contact time between contaminant and soil. Use of higher initial levels of sorbed PCB may show better percent-removals.

Considering the hypothesis that soil treated with multiple extractions to the point such that no further removal would have only a minimum impact on the environment, application of soil scrubbing to PCB-contamination problems may be promising. Available disposal methods for PCB-materials are limited to landfilling in specially approved sites, incineration, and--possibly--some novel processes. Treatment with the soil scrubber prior to disposal may allow relaxation of some of the originally applicable restrictions. It may be possible to scrub the soil and then dispose of the residuals in a sanitary landfill or in a less-than-totally-secure toxic and hazardous site. If the concept of repeated scrubbing to reach a stable soil residual is accepted, the usefulness of the soil scrubber could be almost unlimited.

FURTHER LABORATORY TESTING

Two types of soil contamination exist that can be handled by the soil scrubbing system. The first is a spill situation that involves an immediate response to a freshly spilled chemical-onto-soil system. In this situation, a large amount of contaminant may be physically entrained and only a small fraction actually sorbed to the soil. The goal is then to promptly remove the contaminant into the water phase and replace the soil at the site. The second type of soil/chemical problem is already existing contamination arising from improper chemical disposal. Usually this situation is a longer term problem so that a much larger portion of the contaminant is tightly sorbed to the soil. The goal in this instance is also removal of the contaminant. However, it may be acceptable to mainly remove the mobile fraction and then dispose of the residual soil in less rigorously designed landfills.

The laboratory work concentrated mainly on the more immediate situations and has been used to preliminarily evaluate the treatment of different chemicals and soil types. Using this approach, treatment was found to be most effective for phenol, a water soluble organic compound.

Neither arsenic nor PCB were as effectively treated when considering percent removals. From a removal efficiency standpoint, the soil scrubbing system will probably be most useful for chemicals that have a higher water solubility and a lower affinity for soil than PCB's or arsenicals.

To confirm this result, some additional testing using chemicals with a higher potential for effective treatment should be undertaken. Possible candidates include certain aromatics and heterocyclics, medium chain length organics, and metals (copper, nickel, cadmium, zinc) in cationic states. The program requires an abbreviated version of the preliminary testing performed to date. The same two soil types can be dosed in a manner to simulate spill conditions. Then, a water-knife test program can be undertaken using a set submergence time of 15 or 30 minutes. Finally, the extraction tests can be performed to select solvents and, when appropriate, to evaluate countercurrent extraction. The data obtained from these tests should give a broader indication of the potential range of application of the scrubber for spill and release (remedial) situations.

Another approach to consider involves further investigation of the concept of stabilizing the contaminant level in the soil by scrubbing. To accomplish this, the laboratory approach should be modified somewhat. Existing contaminated soil samples (rather than newly dosed samples) should be utilized in the testing so that the impact of time on soil sorption can be evaluated. Since both PCB and arsenic oxide represent existing soil contamination problems, either or both of these contaminants could be tested. Once samples are obtained, an initial analysis of the contaminant concentration should be made. Then, samples with a range of contaminant amounts can be tested. Some preliminary soil characterization will also be needed. Typical soil testing for particle size, organic and water content, and Atterburg limits would be needed to broadly establish soil types.

The actual tests would be similar to those performed during the preliminary laboratory study. A water-knife test, using the three-stage treatment approach, is the first step. Then, material less than 2 mm can be tested for extraction effectiveness. PCB solvents screened can include water and water plus Tween 80 or other detergents/surfactants. If arsenic is evaluated, then redox solvents may be most promising. The extractions can be performed using successive amounts of solvent until a constant concentration in the solvent is achieved. Then the treated soil can be exposed to the extraction procedure (EP) specified under the Resource Conservation and Recovery Act (RCRA).

When the extract from the EP does not contain contaminants in concentrations more than 100 times the primary drinking water standard, the soil may possibly be classified as non-hazardous. In a full-scale system, disposal to a sanitary landfill or even replacement at the site may then be acceptable, depending upon the situation.

When EP is an acceptable indicator of the soil's contaminant level, this measurement will provide a criterion from which to judge the effectiveness of soil scrubbing. Therefore, further evaluation including the EP procedure would be extremely valuable in assessing the feasibility of the soils-scrubbing concept for any type of soil/chemical contamination.

SECTION 7

DESIGN AND CONSTRUCTION

INTRODUCTION

Upon completion of the laboratory experiments, the treatment sequence for the mobile soil scrubber was finalized. Following is a description of the flow scheme and a discussion of some of the major design considerations. Photographs of the fully constructed prototype soil scrubber components are included within the text.

PROCESS FLOW SCHEME

The sequence of operations for the soil scrubber is as follows (Figure 15). Contaminated soil is deposited into a feeder through a screen that separates oversize material (>2.5 cm). The feeder introduces the soil at a uniform rate into the drum screen scrubber where water knives break down soil lumps and mechanically strip chemicals from the soil. Following initial stripping with recycled wash spray, soil particles greater than 2 mm, which are retained within the drum by the screen, enter the soaking and final rinse zones of the drum before being discharged from the far end of the drum and returned to the site of the excavation or otherwise disposed of. Soil particles of this size dewater relatively easily, and further dewatering beyond that which occurs at the outlet screen of the drum screen scrubber is probably not required.

Particles less than 2 mm, which were not retained within the drum by the screen, form a slurry with the washing fluids, which thickens in the bottom of the wash-spray-collector troughs. This slurry is continuously withdrawn from the troughs and pumped to the countercurrent chemical extractor for further treatment. In the extractor, the soil is processed in a four-step continuous sequence wherein the soil is contacted by washing fluid of increasing purity. The concentration gradient between the chemically contaminated soil and the washing fluid forms the primary driving force for transfer of contaminants into the washing fluid. Within each of the batch chambers of the extractor, the soil/washing-fluid slurry is well-mixed by a froth-flotation technique, which employs both mechanical mixing and fine bubble aeration to achieve good contact between soil and washing fluid. Hydrocyclones are employed between the four stages to partially/sequentially separate the soil from the washing fluid. There is also a hydroclyclone in the solids discharge line at the output of the treatment system. Unlike the drum-screen scrubber, the product of the countercurrent chemical extractor retains a portion of the final rinse water as it exits the underflow of the last hydrocyclone. A drying bed may be necessary before redepositing this portion of the soil at the site, depending on the

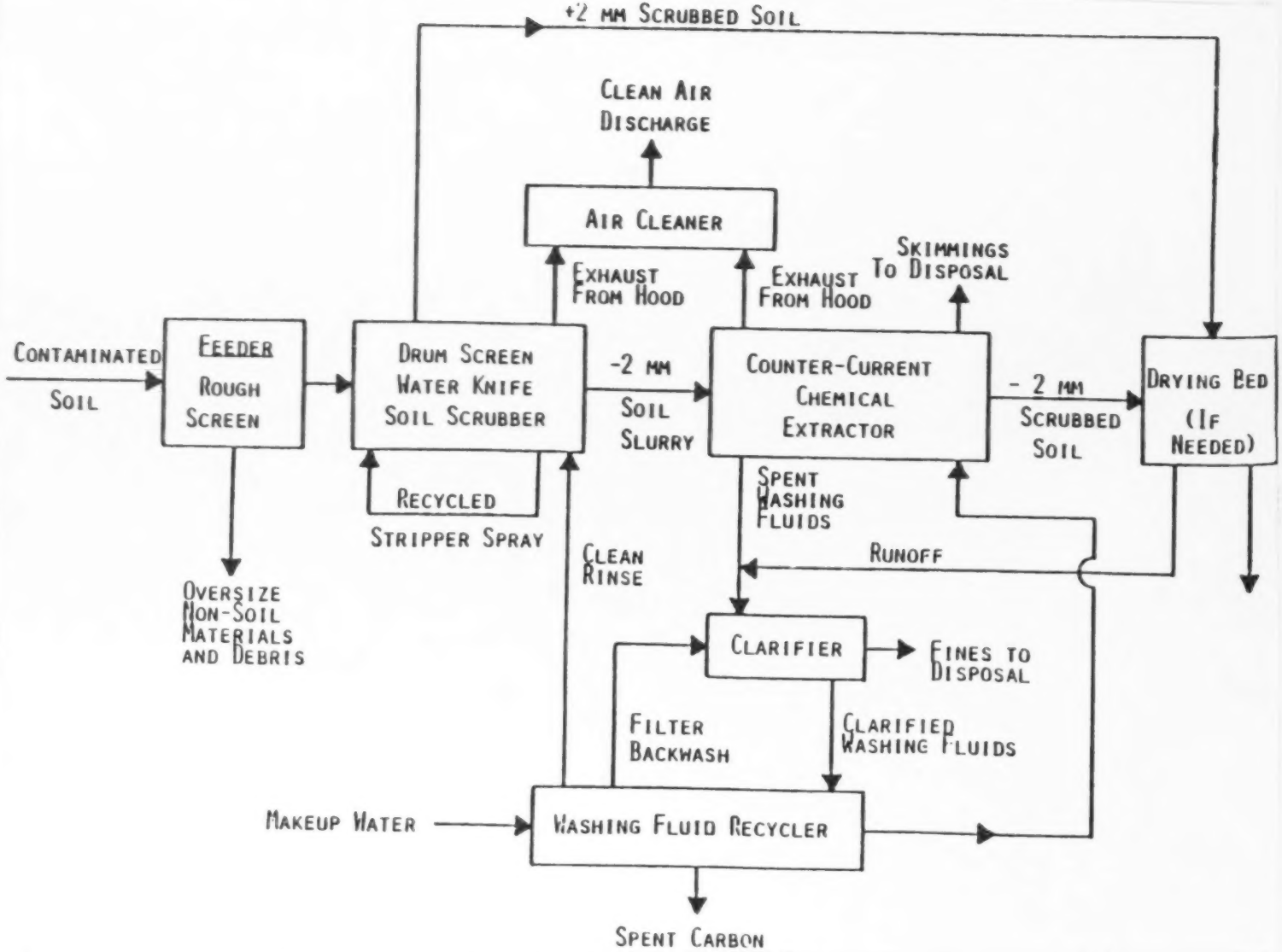


Figure 15. Process flow scheme for soil scrubber.

characteristics of the site and the method for reintroducing the soil.

Likewise, spent washing fluids are also discharged through a hydrocyclone (the overflow of the hydrocyclone in the effluent of the first washing step). Since the hydrocyclone is not fully efficient in removing particles, some of the very fine particles (especially clay) are carried into the spent washing fluid stream. These particles must subsequently be removed by chemical treatment, clarification, and/or filtration prior to introducing the spent washing fluids to carbon adsorption columns or other polishing units where the extracted chemicals are removed before the washing fluid is recycled.

The froth-flotation method of providing intimate contact between soil particles and washing fluids results in the production of a froth, which is skimmed from the top of each of the four extraction chambers. This froth is a treatment residual that must be ultimately disposed of, along with the fines separated from the spent washing fluid.

Froth-flotation can also result in the sparging of volatile chemicals from the wash water. The air discharge from the froth-flotation units, as well as that from the drum screen scrubber (the drum is not a forced-air system but can produce fugitive air emissions), is collected and processed, when necessary, before discharge through a stack.

WATER-KNIFE DRUM SCREEN DESIGN AND OPERATION

Preliminary, small-scale testing during the first phase of this project has shown that thin, intense jets of water from water knives are capable of effectively breaking up even compacted clay lumps, especially when the spraying cycle is combined with a soaking step. Stripping can be effectively accomplished at a water jet pressure of 4.2 kg/cm^2 (60 psi), a low enough pressure to permit direct recycle of stripping fluids without undue problems with nozzle clogging. Tests showed that effective use of water knives also required that the material being stripped be constrained to remain beneath the water knives. Laboratory work demonstrated that the necessary constraint was achieved when the soil was rotated within a drum-like screen.

Mobility Requirements

Initially, efforts were made to procure a commercially available, modifiable rotary screen, that could be converted to accomodate stripping, soaking, and rinsing. Standard trommel screens are expensive and did not meet the design requirements. Extensive modifications would have been required to meet the process objectives. The decision was then made to design a rotary screen specifically tailored to accommodate the stripping, soaking, and rinsing processes.

Since it is advantageous to process as much soil per hour as possible, the largest, practical size drum-screen is desirable. However, since most states limit semi-trailer size to 13.7-m (45-ft) long, 2.4-m (8-ft) wide,

and 4-m (13.5-ft) high, the proposed trailer-borne drum-screen scrubber had to fit within that size envelope for transport without special permits. When allowance in the width is made for sprockets, hoods, drive unit, and piping, the maximum allowable drum shell diameter is about 1.4-m (4.5-ft). The drum-screen unit was thus designed for over-the-road transport without special hauling permits.

After considering various means for transporting and mounting the unit, it was concluded that the best choice was a skid-mounted unit designed for transport on a drop-deck trailer with removal and placement on ground level during operation. The overall dimensions are: 9.8-m (32-ft) long, 2.4-m (7-ft, 10-in.) wide, and 2.4-m (8-ft) high. The empty weight is 6,340 kg (14,000 lb).

Drum Feeding

The loading system consists of a hydraulically lifted bucket, a feed hopper, and a soil metering paddle wheel (Figure 16 and 17). Workers load the bucket with a tractor-mounted front-end loader and rake the soil through a coarse bar screen (ca. 7.5 cm (3 in.)) on the hopper that screens out oversize material. Retained materials can be washed while still on the screen using a hose sprayer, and then removed for final disposal. Soil and liquid passing through the coarse screen fall onto a second bar screen (2.5 cm (1 in.)) where there is additional spraying and removal of chunks too large to drop into the skip hopper. The skip hopper method permits the feeding of soils with any fraction of liquid content, from dry materials to slurries. When the bucket contains a sufficient quantity of material, the operator elevates the bucket above the feed hopper and dumps it hydraulically. This action allows precise control of the dumping rate. The feeding of the hopper is thus under control to prevent overfilling and spillage or clogging. The metering paddle wheel in the feed hopper throat turns at 4 rpm when metering the maximum feed rate of 13.8 m^3/hr (18 yd^3/hr). (The variable speed, paddle-wheel-drive motor permits metering lesser quantities of soil at lower feed rates.)

Drum Screen Construction

Once inside the drum, the soil moves in a controlled fashion from the feed end to the discharge end through a combination of drum inclination and rotational speed. The duration of the three cycles of stripping, soaking, and rinsing is established by the length of drum devoted to each process.

The rotating drum screen soil scrubber unit itself is 6.4-m (21 ft) long and 1.4-m (54-in.) in diameter (Figures 17 and 18). The initial spray zone is a 1.2-m-(4-ft) length of reinforced screen HYCOR Contra-Shear™ that can be backwashed. The next (soaking) section is 4.6-m (15-ft) long and terminates in a baffle having a 0.56-m (22-in.) diameter opening through which the soil and water pass to the rinse zone, which is 0.6-m (2-ft) long and is similar in construction to the initial spray zone. Both screened zones are equipped with water-knife nozzles. The initial spray zone is fitted with 15 internal knife spray nozzles (13 gpm @ 60 psi) and 6 external screen backwash knife elements (10.6 gpm @ 40 psi). The soak zone

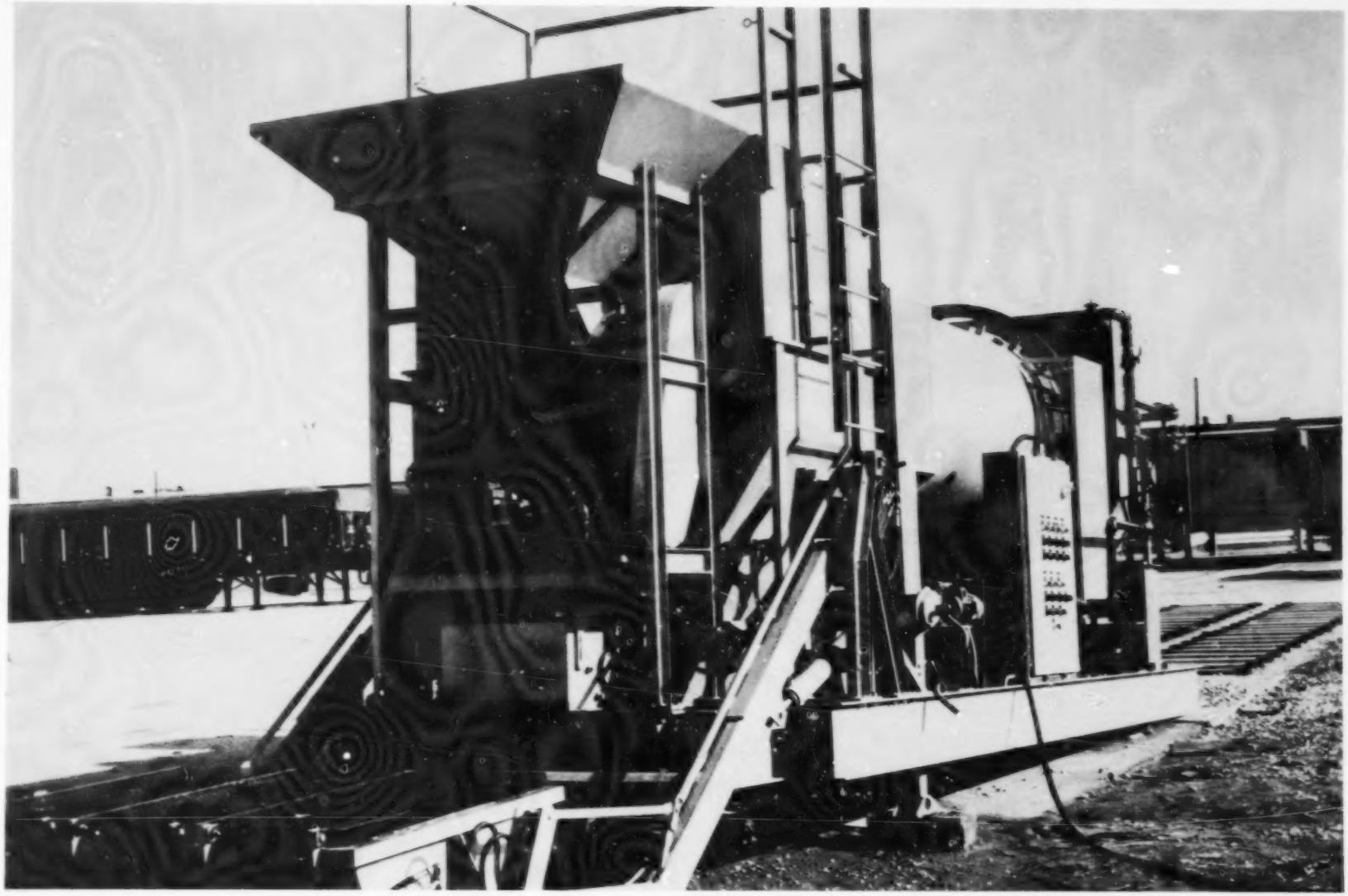


Figure 16. Fully constructed, skid mounted, rotary drum screen scrubber, showing (left to right) hydraulically lifted bucket (ground level), feed hopper (with ladder), water-knife screen and soaking unit (with control panel--center), and scrubbed soil discharge assembly.

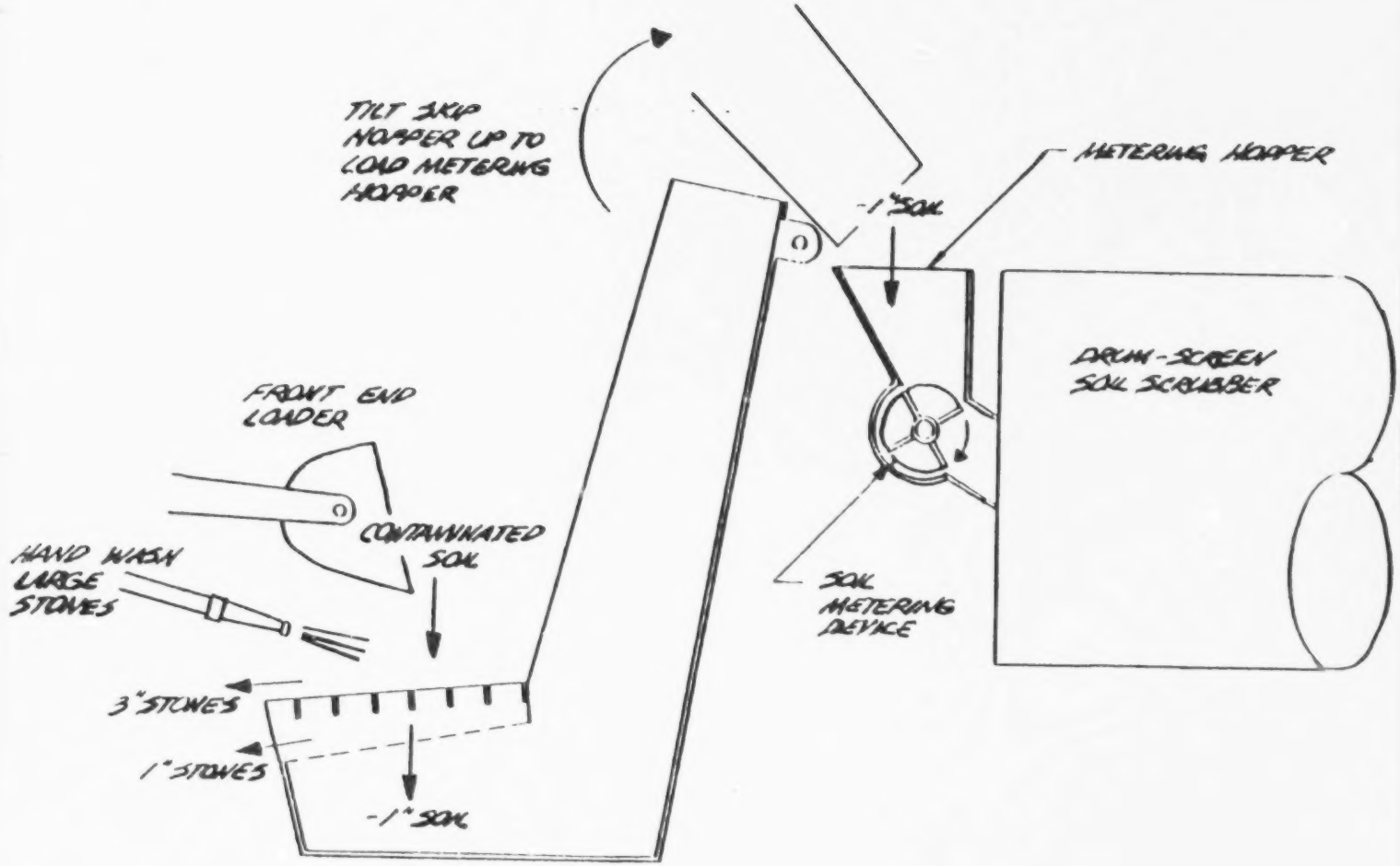
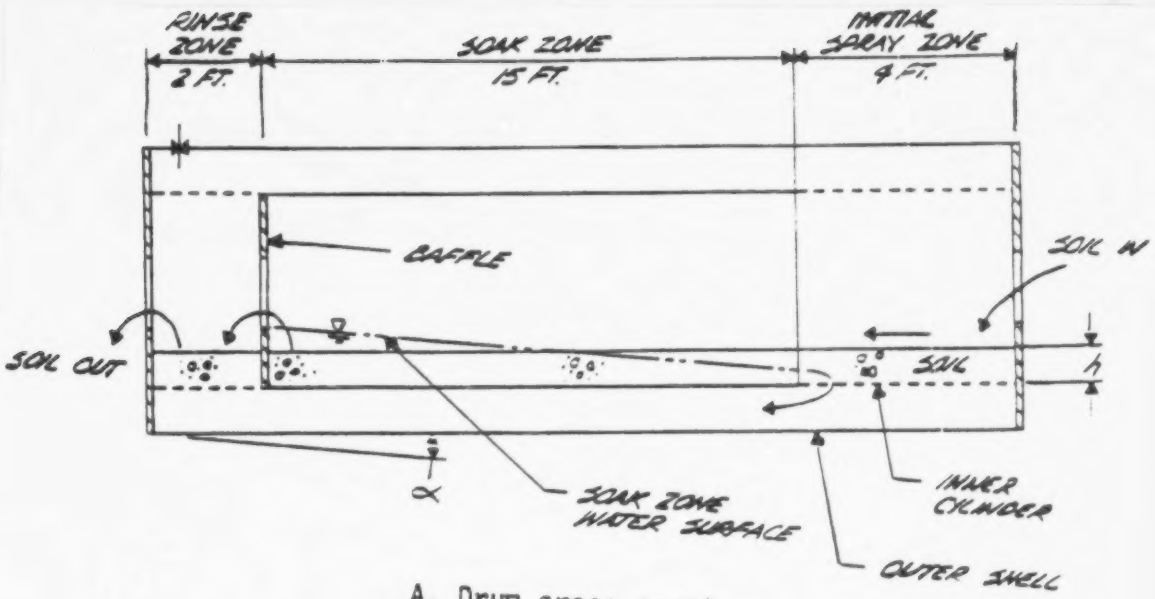
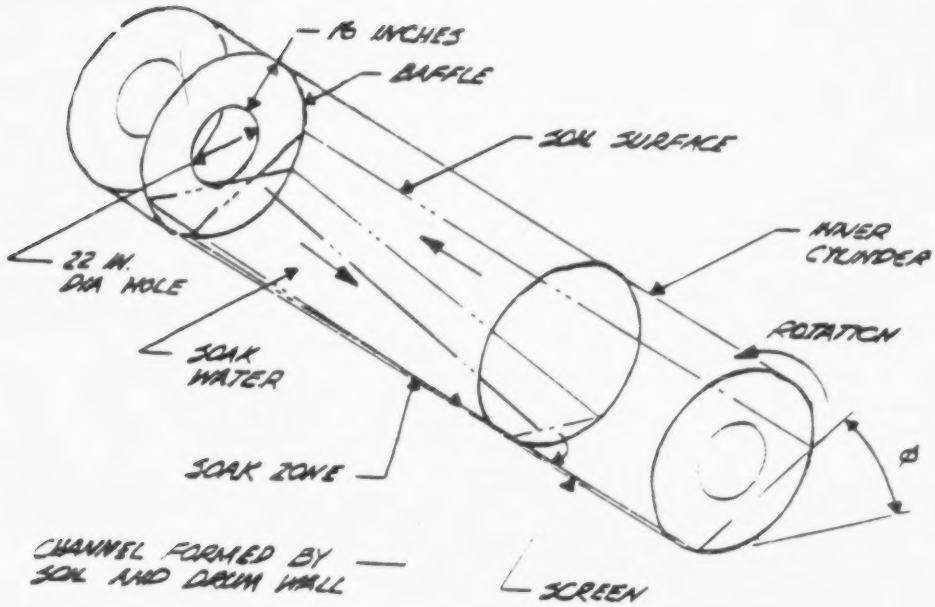


Figure 17. Soil loading and metering system (cross sectional side view).



A. Drum cross section



B. Drum Isometric

Figure 18. Soak zone description.

has one wide angle sprayer (24 gpm @ 40 psi). There are eight 30° full-cone spray-pattern nozzles (10 gpm @ 40 psi) in the final screen rinse section, (1 gpm = 3.785 L/m; 1 psi = 6.9 kN/m^2), some of which can be adjusted for screen backwashing.

Once inside the first screened section (initial spray zone) of the drum, the soil is subjected to water-knife stripping with recycled water. Preliminary tests showed that the minimum stripping time in this section should be one minute; however, because of uncertainties about the cohesiveness of the soil to be scrubbed, the initial stripping was lengthened to four minutes.

The soil then is flushed for 15 min by a countercurrent flow of water in the soaking zone. A baffle separates the soaking zone from the final (rinse) zone. The effective baffle height is determined by drum pitch angle and soil thickness. For a 3-degree pitch of the soil scrubber and a design soil thickness of 22-cm (8.6-in.) at the end of the soaking zone, a baffle height of 41-cm (16-in.) is required. A channel of water is formed by the soil boundary and the drum wall. Soil tumbles into this free-flowing reservoir to be cleansed by flushing and tumbling. Flights are located at the end of the soak zone to lift the soil over the baffle into the rinse zone.

Lower pressure, clean water sprays are utilized to rinse the soil for two minutes in the final screened section of the drum. Clean soil tumbles from the drum into the discharge chute for collection, possible drying, and replacement at the site.

Drum-Screen Capacity

Another design-limiting factor is the capacity of the EPA-ORD mobile physical-chemical treatment system (activated carbon treatment trailer (14)), which is utilized to treat washing fluids for reuse. The nominal processing capacity of the basic granular activated carbon unit is 6.3 L/sec (100 gpm) but can be increased six-fold with lowered residence times. Floc-settle and sand- anthracite filtration processing is part of the treatment process. For many of the soil compositions and conditions that will be encountered, such a rate of wash fluid recycle permits a processing rate of 2.3 to 3.8 m^3/hr (3 to 5 yd^3/hr). However, when the soil contains a large amount of free flowing granular solids (e.g., material from railroad of highway beds), much higher treatment rates, perhaps as great as 13.8 m^3/hr (18 yd^3/hr), are feasible.

COUNTERCURRENT CHEMICAL EXTRACTION UNIT

The principal elements of the semi-batch, countercurrent chemical extractor for soils consist of well-mixed contact tanks and soil/washing-fluid separators (Figures 19 and 20). A simplified schematic of a countercurrent chemical extractor is shown in Figure 20. A soil slurry containing about 10 percent solids is fed and moves through the system in a forward direction (from extraction tank 1 to tank 4) [left to right in Figure 20].

Figure 19. EPA Froth Flotation System (Oily Beach Sand Cleaner) modified as a countercurrent chemical extractor for soil scrubbing, showing (right to left) inlet section (sand hopper in place but not used in this system), four in-series tanks equipped with hydrocyclones and mixing pumps, clean product dischage, Diesel generator.

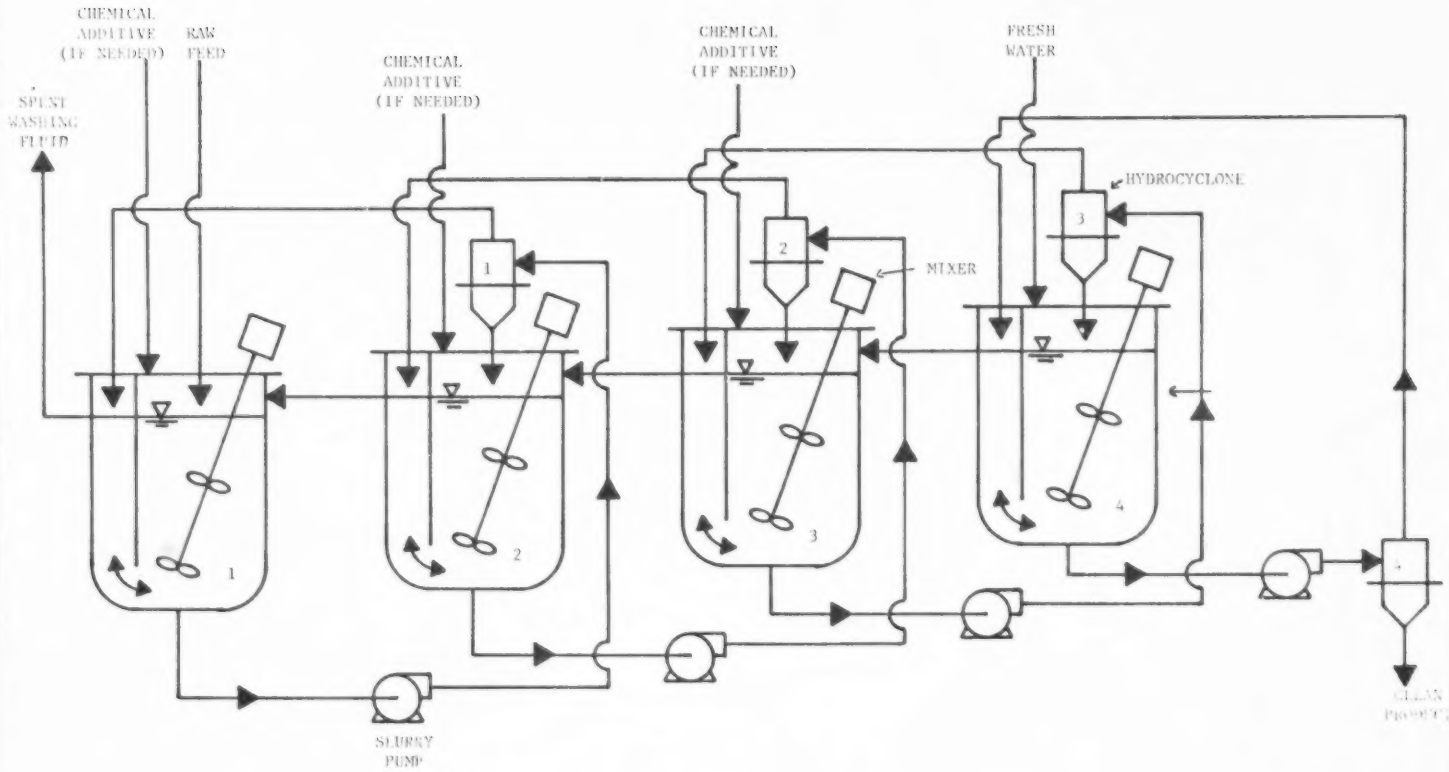


Figure 20. Process flow chart of countercurrent chemical extraction system, showing (left to to right) tank #1 with mixer, raw soil (2mm) slurry feed, and wash fluid discharge: tanks #2 and 3 with mixers and hydrocyclones; tank #4 with mixer, hydrocyclone, fresh washing fluid inlet; clean product discharge hydrocyclone.

Fresh water is introduced at the opposite end of the system (extraction tank 4). The function of tank 4 is to rinse residual contaminant and chemical additives from the soils before the last solid/liquid separation (hydrocyclone 4) and final discharge. Fluid flow through the system is in a reverse direction to the flow of soils (i.e., from extraction tank 4 to 1). Chemical additives may be injected during extraction steps 2, 3, and 4. Following solid/liquid separation (hydrocyclone 1) after the first extraction, the spent washing fluids are removed for treatment and recycle.

Contact Tanks

To be effective, the extraction tanks must provide thorough contact between the soil and the solvent. Mixing enhances this contact and is, therefore, crucial to proper extraction. Two types of contact tanks were considered for the soil scrubber: a propeller-mixed tank and the existing EPA mobile froth flotation unit (oily beach sand cleaner) (Gumtz, 1972). The latter alternative was chosen (Figure 19). Advantages of the EPA-ORD froth-flotation unit are the good mixing potential of the combined pneumatic/mechanical mixing system and the use of a skimming mechanism for removing floating materials and foam. The drawbacks include greater difficulty in control of volatile substances and possible foaming problems when surfactants are used as additives.

Required modifications to the EPA-ORD mobile unit included changing inlet and outlet configurations, mounting hydrocyclones and pumps, coating the tanks to provide chemical resistance, emplacing baffles to reduce fluid short-circuiting, and installing an air contaminant enclosure. The tanks are about 1.7-m (5-ft) high (including sloping bottom), 1.7-m (5-ft) long, and 2-m (6-ft) wide. The modifications are complete; the converted countercurrent chemical extraction unit is shown in Figure 19. (The unit can easily be reconfigured to serve its original function as a beach sand cleaner; indeed, the sand hopper (Figure 20, far left) is not used in the soil scrubbing system but has not been removed.)

System Flow Equalization

A special feature has been incorporated into the system to eliminate problems from non-uniformity in pump flows. Without this feature (unless all of the pumps are perfectly matched in flow), the fluid levels in the tanks would not remain constant and excessive effort to adjust valves manually would be necessary unless complex servo instrumentation was provided. Flow equalization is accomplished by allowing a small amount of fluid to overflow from each tank back to the previous tank, i.e., from right to left in Figure 20.

Solid/Liquid Separation

The preliminary evaluation indicated that hydrocyclones were quite acceptable for the solid/liquid separation step. The hydrocyclones are rubber lined and are all the same size, but do have various size vortex finders and apex valves to accommodate the conditions that exist at each extraction tank. When necessary, vortex finders can be changed in the field.

Washing Fluid Recycle

Washing fluid recycling is essential to reduce operating costs and to make the soil scrubbing concept economically feasible. The spent washing fluid from the countercurrent chemical extraction system is cleaned (treated) and returned to the system. Note that cleaned washing fluid is also needed for the nozzles of the water-knife drum-screen scrubber. The state-of-the-art of treatment of contaminated water is quite advanced; mobile units are already available for these situations. The use of the existing EPA mobile physical/chemical treatment unit with the soil scrubber system is one suitable way of achieving washing fluid recycle capability.

Treatment Residuals

In addition to the debris removed by the initial screening, the residuals from the soil scrubbing system consist of spent carbon in the washing fluid recycle system, soil fines carried out of the soil scrubber with the spent washing fluids, floc-settle and filtration wastes, and foam and skimmings from the froth-flotation tanks.

Emissions of air contaminants from the soil-scrubbing processes are controllable using enclosures and ventilation, followed by air scrubbing or other forms of air cleaning. Some, but limited, fugitive emissions can be expected during soil excavation and feed to the system. Personal protection to prevent inhalation hazards, as well as skin and eye contact, is required for all system operators.

TREATMENT COSTS

For comparative purposes, the costs for scrubbing soil with different levels of phenol contamination have been estimated and are presented in Figure 21. Higher dollar requirements at elevated levels of phenol correlate primarily with the additional expense associated with the cleaning and recycling of washing fluids.

The estimated costs include those for: fuel for the diesel-powered generators that furnish energy to operate the systems, two operators for each process, front-end loader rental, chemical additives, and activated carbon. The estimated costs do not include those for: startup and shutdown, disposal of treatment residuals, maintenance and repair, depreciation, clean water supply, freight, and shipping.

SUMMARY

A mobile system for treating excavated, contaminated soils at a field site by sieving the soil, disintegrating the soil matrix, and cleansing the soil is ready for shakedown, evaluation, and demonstration. The system is expected to take its place among other emerging methods such as in situ treatment or incineration, for treatment of contaminated soils at the actual site of a hazardous substance spill or release under a wide variety of circumstances.

Laboratory work shows that non-aqueous (organic) solvent soil-washing systems have special advantages in processing soils contaminated with highly water-insoluble hazardous substances but that significant design and engineering problems must be overcome to make such systems economically attractive.

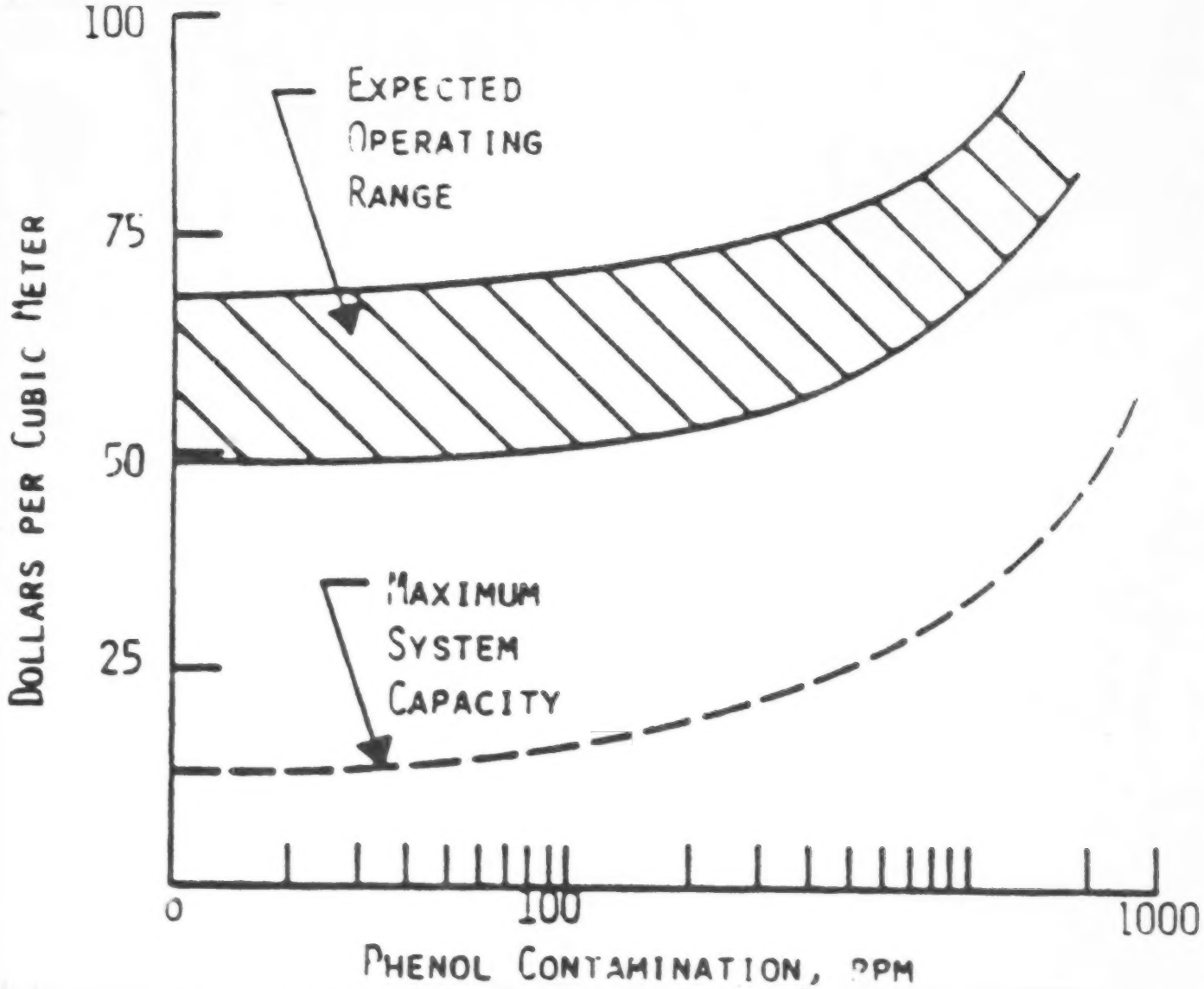


Figure 21. Cost per volume treated for scrubbing phenol from soil.

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